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Energy Analysis of Integrating Carbon Capture for Utilization in a Lignin Extraction Unit at a Swedish Pulp Mill

Master's thesis in Sustainable Energy Systems

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Abstract

Lignin, one of the main components of wood raw material, has significant potential to replace fossil feedstock in a variety of applications. Currently, lignin is often treated as a waste product in pulp production and is primarily combusted for heat and power generation. Södra Cell Mönsterås, one of the largest pulp mills in Sweden, aims to become a global leader in lignin production. The process of extracting lignin from pulp production residues requires carbon dioxide which will be obtained initially from external suppliers at a high price. Hence it is of interest to investigate the opportunity for on-site carbon capture (CC) and utilization from the mill's own emission sources.

This thesis investigates and compares the potential for on-site CC using four different capture technologies, namely absorption with monoethanolamine (MEA), absorption with hot potassium carbonate (HPC), membrane separation and solid adsorption. The main objective of this study was to evaluate the energy requirements for capturing 20 kton of CO_2 per year, which is required for the lignin production. Each CC technology exhibits different energy demands in terms of heating, cooling and electricity. Further aim was to estimate the specific cost for on-site carbon capture and compare with market price of CO_2.

By integrating CC with the mill's energy system, the heat demand can be supplied by steam that would otherwise be used for electricity production. The net electricity loss, defined as the combination of the lost electricity production from the usage of steam and the electricity consumption for CC, was calculated for each technology. HPC presented the lowest net electricity loss at 0.19 kWh/kg CO_2 followed by membrane with 0.22 kWh/kg CO_2, then MEA with 0.23 kWh/kg CO_2 and finally solid adsorption with 0.37 kWh/kg CO_2.

In terms of specific capture cost, the absorption-based technologies were the most expensive due to their high investment costs, resulting in 96 and 142 EUR/ton CO_2 for MEA and HPC, respectively. For solid adsorption, the specific capture cost was 86 EUR/ton CO_2 followed by membrane with the lowest specific capture cost of 44 EUR/ton CO_2. In terms of specific cost, all the studied technologies outperformed the option of externally supplied CO_2, with an estimated cost of 264 EUR/ton CO_2.

The results show that on-site CC can provide a cost-competitive solution to meet the CO_2 demand for lignin extraction compared to externally supplied CO_2. Due to the small scale of the capture requirement, membrane technology is particularly

attractive because of its modular design. In contrast, the economy of scale significantly affects the cost-effectiveness of the other technologies, leading to higher specific capture costs.

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1

Introduction

Global decarbonisation has become an urgent priority with commitment to reducing greenhouse gas emissions in response to climate change. Sweden has set ambitious climate goals to reach net zero emissions by 2045 [1]. One major measure to achieve this is through more efficient utilization of available renewable feedstock to enable substitution of fossil resources.

Södra, one of Sweden's leading forest industry groups, is contributing to this transition by positioning itself as a global leader in lignin production by investing in lignin extraction at the mill in Mönsterås [2]. Lignin, a major component in wood raw material, is currently used as fuel for heat and power production at the mill site. However, lignin holds significant potential as a renewable alternative to fossil-based materials in a variety of applications. By shifting the usage of lignin from energy production to material use, Södra aims to improve its resource efficiency, which is an initiative that aligns with the EU's action plan and strategy for a sustainable bioeconomy [3].

The lignin extraction process itself requires carbon dioxide (CO_2), which is initially planned to be supplied by truck from external sources. However, the pulp and paper industry inherently emits significant amounts of CO_2, presenting an opportunity to capture and reuse this carbon directly on site. Implementing carbon capture (CC) at the mill could not only reduce the cost of obtaining CO_2, but also create a more circular and self-sufficient system. Today, there exists a wide variety of different CC technologies, each with different level of technical maturity, integration complexity and energy demand [4]. Since energy use is a key factor affecting both the environmental and economic performance of CC, understanding the energy implications of different capture technologies is essential for selecting the most suitable option.

At the mill in Mönsterås, there exists three major emission sources with different sizes and specifications. The recovery boiler is by far the largest emission source but with a significantly lower CO_2 concentration than the two lime kilns at the mill. Generally, higher CO_2 concentrations results in lower energy demand for CC, but is far from the only aspect to consider. Different CC technologies can also impose for example health concerns and sensitivity to flue gas impurities which needs to be considered. Regarding the energy requirement for CC, it is important to investigate and understand the energy system within the mill in order to evaluate the potential for CC. This thesis investigates the feasibility of integrating on-site CC at the mill in Mönsterås, with a specific focus on the energy requirement of different CC technologies.

1.1 Aim and Objectives

The aim of this project is to analyze the potential for integration of a CC process at the pulp mill Södra Cell Mönsterås in order to internally supply CO_2 for the planned lignin production plant at the mill site. More specifically, the aim is to investigate the heat and power requirements for different post-combustion CC technologies. These technologies will be sized to deliver the required amount of CO_2 to the lignin extraction process and then assessed based on their advantages and disadvantages for CC at the mill.

To achieve the aim of this work, the following objectives have been formulated:

- Qualitatively compare advantages and disadvantages of different post-combustion CC technologies suitable for partial CO_2 capture from lime kiln flue gases for the purpose of utilizing CO_2 for lignin extraction
- Quantitatively evaluate energy demand for the different technologies to meet the CO_2 demand for lignin extraction
- Investigate different integration possibilities between the CC unit and the mill based on steam and electricity requirements
- Estimate capital- and operational expenditures for CC integration compared to market price of CO_2
- Identify knowledge gaps and provide recommendations for further research

1.2 Limitations

The focus for this project is the energy requirements of the different CC technologies, rather than their chemical and mechanical functionality and applicability. With the extensive availability of CC technologies it was decided to only look at post-combustion CC technologies, since they would minimize the impact on the pulping process. Furthermore, the focus is on four different types of commercially available technologies, namely, two absorption-based, one membrane-based and one adsorption-based. Approximately 20 kton of CO_2 is required annually for the lignin extraction process. Although it could be beneficial to invest in a larger CC facility, the main objective of this project is to investigate different opportunities to meet the specified CO_2 demand.

At this stage, the specifications for the lignin extraction process assume that CO_2 is supplied with high purity. Consequently, it was decided that the captured CO_2 should have a purity of 95% or higher to meet this specification. This also facilitates data collection since many studies aim at purity $\geq$95%. Although it may be possible to use CO_2 with a lower purity, this option is not the primary focus of this work and will not be pursued further.

2

Background

This chapter provides a general background to the pulp industry with a short description of the kraft pulping process along with the chemical recovery cycle and the lignin extraction process. Rather than an in-depth exploration, it presents an overview of these topics and thus directing interested readers to other sources for more detailed information. In addition, the chapter also provides a description of the different CC technologies considered during the project.

2.1 Pulping process

This section provides a general overview of the most common pulping process in Sweden, the kraft pulping process, along with some background of the chemical recovery cycle and the lignin extraction process.

2.1.1 Kraft pulping process

The most common process for production of wood pulp in Sweden is kraft pulping (or sulfate pulping), also being the process used at the Södra mill in Mönsterås [5]. The main objective of the kraft pulping process is the removal of lignin, which makes up about 30% of the raw wood material [6]. Logs that arrive at the mill are debarked and chipped before entering a digester. In the digester, the wood chips are cooked together with a mixture of chemicals called white liquor (mainly consisting of NaOH and Na_2S). During digestion, the lignin is dissolved in the liquid phase, leaving the cellulose fibers in the solid phase. The resulting mixture now consists of a liquid called black liquor (spent cooking chemicals and lignin) and a solid phase called pulp (the cellulose). After cooking, the pulp is separated from the black liquor and is then washed in several steps to recover more chemicals and remove impurities. The pulp is then sent to further treatment including bleaching, drying and packaging before being sold to the customer. The black liquor from the digestion section is sent to the chemical recovery system.

2.1.2 Chemical recovery

To enable the reuse of cooking chemicals in the kraft pulping process, a chemical recovery system is implemented [5]. The black liquor from the digesters is first sent to evaporators where the water content is decreased and then it is sent to the recovery boiler at the mill. In the recovery boiler, the organic matter in the black liquor (mostly lignin) is combusted to enable steam generation. During the process in the recovery boiler, the chemicals in the black liquor form a smelt that is collected in the bottom of the boiler. The smelt is then removed from the boiler into a dissolving tank where it is mixed with diluted white liquor to form green liquor. The green liquor is sent to the causticising plant and is then mixed with burned lime mud to form white liquor and slaked lime ($CaCO_3$). The white liquor can then be used again for pulp production in the digester while the slaked lime is transported to the lime kiln where it is burned to regenerate calcium oxide according to Reaction 2.1.

$$\mathrm{CaCO_3} + Heat \rightarrow \mathrm{CaO} + \mathrm{CO_2} \tag{2.1}$$

Reaction 2.1 is endothermic thus heat is required to produce calcium oxide which is provided through combustion of carbon containing fuels. The flue gas stream from the lime kiln will typically have a high concentration of CO_2 (around 20%-wet), because there will be formation of carbon dioxide both from the combustion of fuels and from the calcination Reaction 2.1. A schematic overview of the chemical recovery cycle can be seen in Figure 2.1.

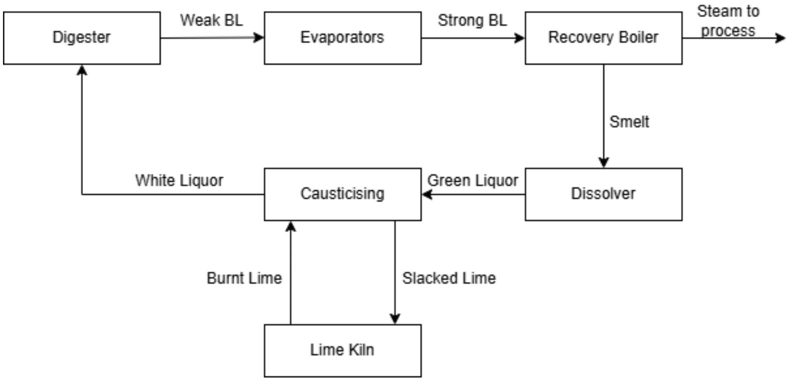


Figure 2.1: A schematic overview of the chemical recovery process.

2.1.3 Lignin extraction process

To utilize the wood raw material more efficiently, lignin can be extracted from the black liquor and replace non-renewable products instead of being used as fuel at the mill site [7]. The capacity of the recovery boiler is usually a bottleneck in a kraft pulp mill, which means that the amount of pulp that can be produced is limited by the amount of biogenic material in the black liquor that can be combusted in the recovery boiler [5]. Since lignin extraction can help off-loading the recovery boiler by reducing the content of combustible material in the black liquor, lignin extraction can also enable increased production at a mill where production is constrained by recovery boiler capacity. A schematic overview of a lignin extraction process can be seen in Figure 2.2, which is based on the LignaRec process from Andritz [8], but there is also a commercial lignin extraction process available from Valmet [9] and Noram [10].

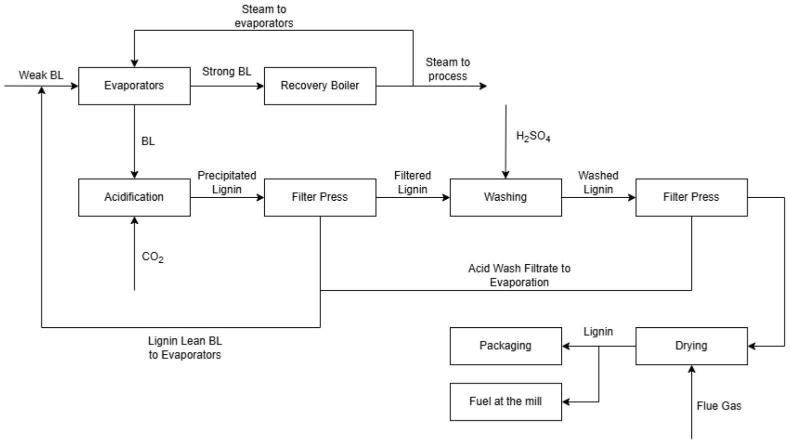


Figure 2.2: A schematic overview of the lignin extraction process based on the LignaRec technology by Andritz.

The lignin extraction process starts with a stream of black liquor from the evaporation plant entering an acidification reactor [8]. The size of the black liquor stream from the evaporation plant is determined by the capacity of the lignin extraction unit. The acidification of black liquor utilizes CO_2 to lower the pH [6]. When the pH is lowered, the lignin starts to precipitate from the black liquor and can thus be separated using a filter press. The lignin is then washed using sulfuric acid to remove impurities such as sodium. Finally, the lignin is dried prior to being packed and stored for transportation to costumers. Prior to drying the washed lignin is dewatered further using a filter press and then excess heat available at the mill, for example, flue gas streams. The remaining black liquor (with lower lignin content) after lignin extraction will be sent back to the evaporators together with acid filtrates from the lignin wash in order to ensure recovery of cooking chemicals and make use of the remaining energy content.

2.2 Carbon capture technologies

CC is a key technology for reducing CO_2 emissions and mitigating climate change. One of its main usages is to capture carbon dioxide from flue gases in different industries before it is released to the atmosphere. The carbon dioxide can then either be permanently stored (carbon capture and storage - CCS) or used as a feedstock for other applications (carbon capture and utilization - CCU). CC methods can generally be categorized into three main approaches based on when and how the carbon is captured [11]. Firstly, post-combustion CC involves separating dilute carbon dioxide from flue gases after combustion of carbon-containing fuels. Secondly, there is pre-combustion CC, which works by gasification of carbon-containing fuels. The gasification produces CO_2 and H_2, and thus the CO_2 can be separated and stored and the H_2 can be used as carbon-free fuel. Finally, there is oxy-fuel combustion which works by combustion of fuels with pure oxygen in order to have a flue gas stream consisting of almost only CO_2 and H_2O vapor, the steam can then be condensed to generate a pure CO_2 stream.

Post-combustion CC processes are often very energy consuming because of the low concentration of carbon dioxide in the flue gases. Furthermore, contaminants in the flue gases can become a problem by causing degradation of chemicals used in the CC process. However, post-combustion capture is the most established approach for CCS/CCU applications since it is very flexible and therefore enables implementation in existing CO_2 emitting processes. Because of the greater potential for retrofit, only post-combustion CC technologies have been considered during this work.

The post-combustion CC technologies to investigate in this master thesis project were selected in dialogue with Södra. The decision was based on the assumed purity required for the CO_2 product and the intended CO_2 utilization, which does not require liquefaction of the CO_2. It was also decided that CC technologies with different working principles were to be investigated in order to cover a wider variety of possibilities. The first technology is one of the most common and researched methods today and utilizes absorption by amine-based solvents to capture the CO_2. In this work monoethanolamine (MEA) is investigated. Although this technology is one of the most widely used today, it requires large amounts of energy in the form of heat, and the amine solvent is associated with health and environmental concerns [12] [13]. An alternative absorbent that can be used for CC is hot potassium carbonate (HPC) which has some advantages compared to MEA. In a HPC process, pressure differences in combination with temperature differences are utilized to release the absorbed CO_2, which reduces the heat requirements [14]. Another interesting technology is adsorption-based capture which also has low heating demands [15]. Lastly, another emerging technology is membrane separation, and although it is not as developed as absorption-based CC and is associated with low degrees of separation, this technology has shown potential to separate CO_2 at lower energy demand compared to other technologies [16]. This work aims to investigate these different CC technologies and assess their compatibility for lignin production from an energy point of view.

2.2.1 Absorption

Absorption is a commonly used process for CC [17]. The general principle of absorption-based CC is that CO_2 in the flue gases is absorbed by a solvent. This is done by letting flue gases, containing CO_2, enter the bottom of an absorption column while the solvent is sprayed from the top [18]. The CO_2-lean flue gases exit from the top of the absorber, and the CO_2-rich solvent from the bottom. After the absorption column, the CO_2-rich solvent is pumped to a stripper where the solvent is regenerated (CO_2 is desorbed). In this project, two different types of absorption-based CC technologies are be investigated, one utilizing a temperature swing and the other utilizing a combined pressure and temperature swing. A temperature swing means that the temperature is changed between the absorber and desorber depending on which temperature favors the desired reaction. For the pressure swing it is the pressure that changes instead of the temperature.

2.2.1.1 Monoethanolamine - MEA

The potential for using monoethanolamine (MEA) for CO_2-capture has been known for decades [19]. It functions with temperature as the driving force (temperature swing) where the flue gases and solvent enter the absorption column at a low temperature to allow absorption [18]. The solvent is then regenerated through heat addition in the desorption step. The CO_2-lean solvent leaves the stripper from the bottom and enters a reboiler where steam is supplied to generate the heat, the amine solution is recovered and transported back to the absorber. The CO_2 product exits the top of the stripper and enters a condenser where water vapour is removed. To ensure efficient use of energy, a heat exchanger is used to recover heat from the hot CO_2-lean stream exiting the stripper and supply it to the cold CO_2-rich stream from the absorber. A schematic overview of a process for absorption-based CC using a temperature swing can be seen in Figure 2.3.

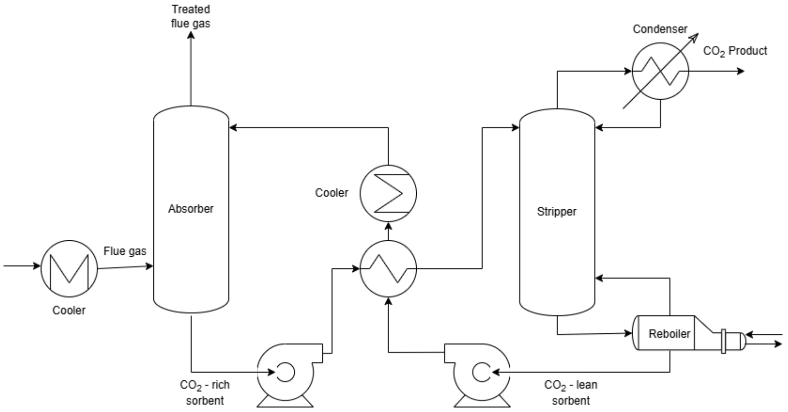


Figure 2.3: Schematic overview of absorption-based CC technology using MEA.

MEA is the most commonly used amine solution for CC in industry [20]. This is because of the many advantages for CC technologies using MEA such as low investment cost compared to other absorption technologies, potentially high capture rate and high CO_2 product purity. However, this comes at a high cost in the form of energy requirements for solvent regeneration, which results in lower energy efficiency. Furthermore, amine-based solvents, such as MEA, have been shown to be associated with health concerns since carcinogenic substances are released during MEA degradation [21]. There are several reasons for degradation of MEA solvents, for example, elevated concentrations of oxygen, NO_x and SO_x all contribute solvent degradation [22]. The degradation of solvent is not only related to health concerns but it also comes at a cost since with degradation of solvent there is a requirement for a stream of fresh solvent makeup. MEA is just one example of an amine-based absorption solvent, there exist a large number of so-called "advanced amines", many suppliers of CC technology offering their proprietary mixture of amines aiming for reduced energy consumption and/or increased stability against degradation.

2.2.1.2 Hot Potassium Carbonate - HPC

HPC CC technology provides an alternative absorption strategy that is not relying on amines and thereby avoids the associated health and environmental issues of amine-based absorption. Instead of only using a temperature swing for absorption-desorption, a combined pressure and temperature swing is used, which reduces the heat requirements but increases the electricity demand. In the absorption column, the flue gas enters at a pressurized state which allows the absorption process to operate at a considerably higher temperature than the atmospheric boiling point [23]. The pressurized CO_2 is absorbed together with water by potassium carbonate and forms bicarbonate. The bicarbonate is then depressurized and enters a stripper equipped with a reboiler which supplies energy in the form of steam. Under these conditions the bicarbonate reacts back and forms potassium carbonate, releasing CO_2 and water. A steam/CO_2 mixture gets extracted from the top of the stripper while the potassium carbonate is pressurized and sent back to the absorption column. The steam/CO_2 mixture is then sent to a condensor to reduce the water content and pressurized to generate high purity CO_2 [24]. A simple schematic of the HPC system is presented in Figure 2.4.

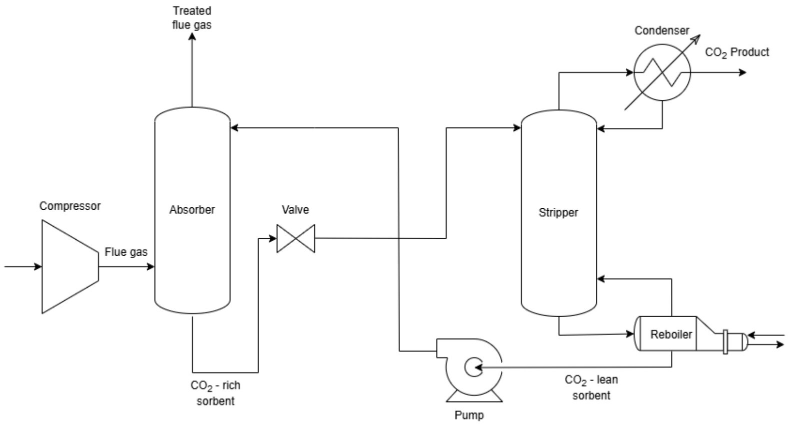


Figure 2.4: Schematic overview of absorption-based CC technology using HPC.

The use of a pressure swing reduces the heat required for solvent regeneration. However, there are some concerns regarding a capture rate of over 90% because of the high amount of electricity needed for high-pressure operation [14]. Implementing a HPC process results in a large energy penalty in terms of electricity consumption compared to other absorption-based CC technologies, which makes it less suitable for systems with power production as the primary output [24]. Increasing the pressure may also raise concerns about impurities in the flow. For example, the presence of water combined with CO_2, SOx, and NO_2 can form corrosive acids, potentially damaging the compression equipment [25]. However, HPC presents a great opportunity for heat recovery, making the technology very suitable for processes that are connected to a district heating system or other systems requiring heat at similar temperature levels.

2.2.1.3 Alternative Solvents

MEA and HPC are just two examples of solvents that can be used for absorption-based capture, which here have been used to represent options for temperature-swing and pressure-swing absorption respectively. There are however a wide variety of different solvents for absorption-based CC [4]. Different solvents can have different advantages such as lower energy requirement for regeneration or better resistance to degradation.

2.2.2 Membrane

The membrane-based CC, unlike absorption, is neither dependent on chemical reactions nor highly energy intensive in terms of heat demand [26]. The membrane CC technology utilizes a selective membrane that separates components with different properties. The driving force for this separation technology is a pressure difference that will force the desired component through the membrane [27]. Because of the absence of chemical additives, it is seen as a more environmentally friendly technology since there is less risk for pollution. Membrane CC technologies also have several other characteristics that can be beneficial under different circumstances. Due to the modular configurations, membranes are highly flexible and can work well on both large and small scales. Furthermore, to achieve the desired capture rate and gas purity, different configurations, where the gas passes through multiple membranes in different steps, can be utilized [28]. A simple schematic overview of a two-stage membrane CC process with recirculation is visualized in Figure 2.5.

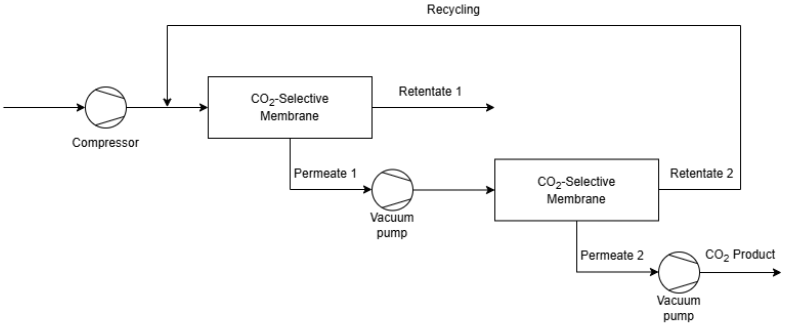


Figure 2.5: A schematic overview of a simple two-stage membrane CC process with recirculation.

With the two-stage membrane configuration shown in Figure 2.5, which includes recirculation, high CO_2 purity can be reached in the product stream. The product purity that can be achieved with membrane technology is not only dependent on the membrane configuration but also the CO_2 concentration of the inlet flue gas. Lower feed CO_2 concentration might require more membrane stages or increased pressure ratios over the membranes which will result in increased energy demand [29]. Also, as can be seen in Figure 2.5, there is no heating demand for the CO_2 capture process but there will be a cooling requirement associated with compressor cooling and cooling of the flue gas to the appropriate inlet temperature for the membrane.

Today there exists a large variety of membrane materials with different properties. The selection of a suitable membrane material for CO_2 separation depends primarily on the CO_2 permeance and selectivity of the material [26]. Membranes with high permeability are required to achieve a high CO_2 flux and hence a high capture rate. On the other hand, membranes with higher selectivity can provide higher purity of the separated CO_2.

As mentioned above, there is no heat requirement for the membrane CC. However, there is an electricity requirement associated with generating the driving force, i.e. the pressure difference, across the membrane. The electricity requirement is dependent on several factors, including CO_2 inlet concentration, desired CO_2 purity and membrane configuration, but is usually higher than for absorption-based CC technologies [28]. Even though the advantages of membrane CC technology are plenty, there is still a lack of acceptance from industry. This is because of the low technology readiness level (TRL) of many membrane technologies along with a significant gap between research and industrial application [26]. This is usually because it is difficult to create membrane materials that have both good permeability and selectivity while being cost effective. Furthermore, there are currently major challenges to creating durable membranes that can also handle impurities like particles, SO_x and NO_x without rapid deterioration, which is a major focus in developing future membranes [29].

2.2.3 Solid adsorption

Another CC technology is solid-based adsorption, which is still under development and currently has very few suppliers available[4]. Adsorption means that molecules stick to the surface of the adsorption material as a result of either chemical bonds or physical forces. The molecules can then be released by changing the conditions, for example with change of temperature [30]. The materials used for adsorption-based CC are many, for example, metal organic framework (MOF), organic polymers, inorganic adsorbents and silicon-based adsorbents [31].

MOFs consist of metallic clusters together with organic linkers to stabilize and create a porous material. The advantage of MOF is that, with the organic linkers, the pore size can be tuned to better capture the specific substance of interest. The method is primarily used for gas separation and usually uses a temperature swing for regeneration [31].

It has been shown that solid adsorption can achieve CO_2 purities of up to 95% with high selectivity over water. When using the MOF adsorbent CALF-20, the system also demonstrates resistance to common flue gas impurities such as SO_2, NOx, and oxygen [32]. The CALF-20 material is fabricated into thin sheets and assembled into structured, modular beds used in the CC plant. There are two operational alternatives for these modules: batch or continuous processing. However, in this thesis, only continuous operation is considered, a concept that is marketed by the company Svante [32]. In the continuous setup, the beds are placed inside a rotating machine that cycles through three stages—adsorption, regeneration, and conditioning. During the adsorption stage, flue gas is passed through the modules, allowing contact between the gas and the MOF material, which binds CO_2 molecules. This adsorption process is exothermic and raises the temperature of the bed. To ensure efficient capture, flue gas conditioning is often required beforehand, primarily to adjust the temperature. In the second stage, regeneration, the system rotates the beds into a separate chamber where low-pressure (LP) steam is introduced. This releases the captured CO_2 from the material, primarily due to the change in partial pressure, but also aided by the heat from the steam. Additionally, the adsorption of steam is more exothermic than that of CO_2, which further drives the displacement of CO_2. The result is an output stream primarily consisting of CO_2 and steam, which is later condensed to produce a high-purity CO_2 product. Finally, in the conditioning stage, the beds must be cooled back to adsorption temperature and any residual water vapor removed. Heated air is used for this purpose, cooling the bed while preventing water condensation. The cooling occurs due to both the lower temperature of the air relative to the bed and the endothermic nature of water desorption [33] [34]. A schematic overview of the CC process using solid adsorption system is shown in Figure 2.6.

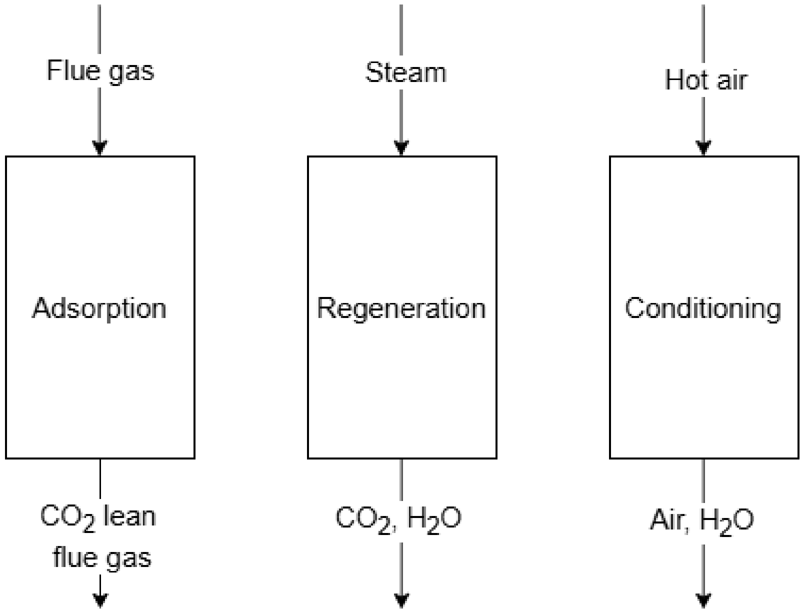


Figure 2.6: Schematic overview of a solid adsorption CC process.

3

Case Study

This chapter provides an overview of the studied pulp mill, namely Södra Cell Mönsterås. It also presents the existing steam network and predicts changes due to lignin extraction. Furthermore, an overview of the secondary heating system and emissions considered for CC are provided.

3.1 Södra Cell Mönsterås

Södra Cell in Mönsterås is one of the largest pulp mills in Sweden with a capacity of 750 kton pulp per year. Pulp is produced in Mönsterås from both hardwood and softwood, but since there is only one production line, the mill runs in different campaigns. The mill operates differently depending on whether it is a hardwood or softwood campaign. One major difference between the campaigns is that with the lower lignin content of hardwood, there is less black liquor available to fuel the recovery boiler, and consequently lower steam production during the hardwood campaigns. At the mill, there is also a power boiler available for steam production. The power boiler utilizes bark that is removed and dried during pretreatment of the logs before the pulping process. The load of the power boiler can be altered depending on the steam demand in the process, the electricity price and the fuel availability.

The mill in Mönsterås is equipped with two lime kilns that produce burnt lime for the causticizing plant. The fuels used in the lime kilns are mainly bark powder and tall oil. The two lime kilns operate very similarly, with the main difference being the size and hence the capacity to produce burnt lime. The reason for having two lime kilns is that the capcity of the mill has been expanded over time, and in one such expansion project it was decided that it would be beneficial to keep the old lime kiln in order to lower the investment cost of the new one. Having two lime kilns is sometimes favorable since the process can continue for some time even though one of them needs to be stopped for maintenance or failure in operation.

Apart from the production of pulp, several other products are produced at the mill in Mönsterås, for example, tall oil and turpentine, which can both replace fossil materials in several applications. Since 2020, the mill also produces biomethanol, which can be sold as a biofuel. Currently, a lignin extraction facility is under construction with capacity to extract 200 tons/day of lignin from the black liquor. The extraction of lignin from black liquor will affect the steam network at the mill as will be seen in Section 3.2.1.

3.2 Steam Network

The steam network at Södra cell Mönsterås is schematically represented in Figure 3.1. The steam network consists of five different pressure levels. The recovery boiler (SP6) together with a power boiler (ÅP5) produces high pressure steam at 62 barg and 475 °C that is supplied to the high pressure steam header (ÅH). Inside the recovery boiler, steam at 26 barg is required to remove soot from parts of the equipment. This steam is extracted as a side stream at 26 barg from the recovery boiler during the boiling process.

During current operations, a significant amount of primary steam is expanded to the 3 barg steam header (ÅL3) through turbines G4 and G5. This steam is used, for example, in the evaporators, digesters and for heating feed water. The 5 barg steam header (ÅL5) is supplied by steam from turbine G3, which is mainly used for pulp drying. The demand from the dryers can vary on an hour-to-hour basis because of varying moisture levels making it unnecessary to always provide 5 barg steam. Because of this, the pressure in the 5 barg steam header is often lower than 5 barg and can drop to as low as 3 barg while still supplying the required steam to the dryers, while also increasing electricity production with turbine G3. The next pressure level is 11 barg (ÅM11), where G3, G4 and G5 are all connected, but the majority of the steam in this header is supplied through the extraction from turbine G3. The steam from ÅM11 is used, for example, in all digesters and the recovery boiler. Unlike the ÅL5 steam header, the pressure of this steam is stable at 11 barg. The reason for this pressure stability is the demand from the recovery boiler which requires a constant pressure of around 11 barg. Lastly there is a 17 barg steam header (ÅM17) with steam provided by an extraction at turbine G5. This header has the smallest flow among the steam headers and is only connected to the bleaching section.

As shown in Figure 3.1, there is a fourth turbine, the condensing turbine G6. The load of the back pressure turbines is decided by the steam demand at the different pressure levels at the mill. Because the recovery boiler and power boiler produce more steam than is required at the mill, turbine G6 was built to utilize the full steam production and thus maximize electricity production.

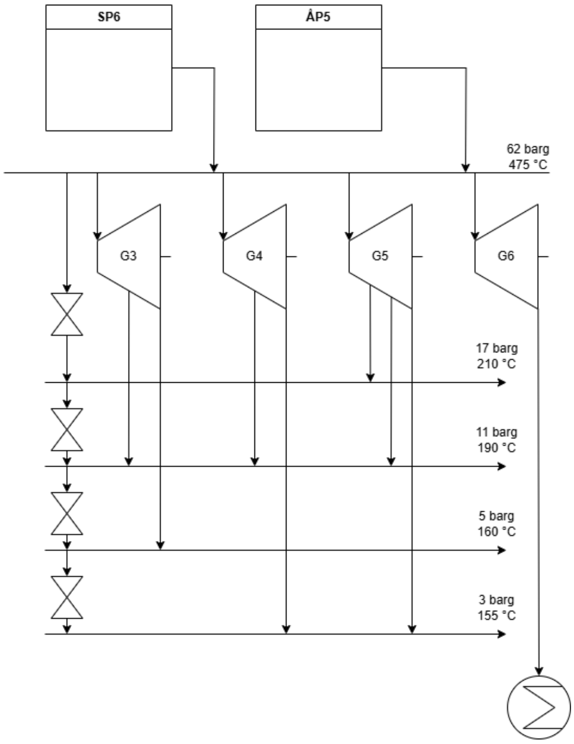


Figure 3.1: Schematic overview of the different steam pressure levels with the steam extractions from the turbines at the mill in Mönsterås.

3.2.1 Effect of Lignin Extraction on the Energy System at the Mill

When lignin is extracted from the black liquor there will, as earlier mentioned, be less fuel availability for primary steam production in the recovery boiler. Another factor that will change the steam availability is that the extracted black liquor will return to the evaporation plant after lignin extraction with increased water content which will increase the load of the evaporators. This will mean that an increased amount of LP steam will be needed for the evaporation section at the mill and hence increased load on turbine G5 and decreased load on turbine G6. Table 3.1 shows the calculated decreased steam availability considered with the implementation of the lignin extraction plant with literature data from [35].

Table 3.1: Calculated changes in the steam balances at the mill after the implementation of lignin extraction.

Primary steam production loss	18 kg/s
Increased LP steam load	1 kg/s

The steam network described in Section 3.2 represents the current steam network before the implementation of the planned lignin extraction plant. The lignin extraction plant is designed so that the steam production loss is smaller than the excess primary steam previously used for electricity production in turbine G6, which has been operating close to maximum load. However, this will cause the G6 turbine to operate closer to its minimum capacity and may require it to be temporary shut down during certain operating conditions, such as during hardwood campaigns in winter season.

3.3 Secondary Heating System

The mill in Mönsterås is equipped with an extensive secondary heating system. The water in the secondary heating system serves as both hot and cold utility. The demand for hot and cold water is not continuous, so the water is stored in tanks at different temperature levels. There are three main water tanks, one containing cold water at approximately $12°C$, one with warm water at about $55°C$ and the final tank holding hot water at around $85°C$. Currently, the mill has an excess of warm water that could be used as utility. Hot water, on the other hand, is more valuable and could be utilized further in the mill. Therefore, increasing hot water production would be beneficial. A more detailed description of the secondary heating system can be found in [36].

3.4 Emissions

The mill in Mönsterås has several emission sources, each with different flue gas flow rates and compositions. Although the recovery boiler is the primary source of CO_2 emissions at the mill, this project focuses on emissions from the lime kilns. This is due to the higher CO_2 concentrations, which are advantageous in terms of energy consumption for CC. The CO_2 emissions from the lime kiln originate partly from fuel combustion to generate the required heat for calcination and partly from the chemical reaction where calcium oxide is formed from slaked lime as can be seen in Equation 2.1. Flue gases from lime kiln 1 will be used to dry the lignin after the extraction from black liquor, lowering the temperature of the flue gas stream. However, the composition of the flue gases is assumed to remain unchanged during the lignin drying process. As will be seen in Section 4.1, the inlet temperature for the flue gases to the CC plant will be much lower than the outlet temperature from the lime kilns. This will make it favorable to capture CO_2 from the flue gases from lime kiln 1 after the ligning drying section since this will lower the overall cooling duty for the CC plant. Tables 3.2 and 3.3 provide an overview of emissions from lime kiln 1 and the flue gas compositions.

Table 3.2: Overview of flue gas from lime kiln 1 at the mill.

Flue gas flow (Nm^3/s)	Flue gas temperature(°C)	Flue gas temperature after lignin dryer (°C)
16.0	220	95°C

Table 3.3: Flue gas composition from the lime kilns at the mill.

CO_2 (%wet)	O_2 (%wet)	H_2O (%wet)	N_2 (%wet)	H_2S (mg/Nm^3)	NO_2 (ppm)	SO_X (ppm)
18.9	3.5	30.0	47.6	2	108	<1

4

Methodology

This chapter describes the methodology of this project. The project was divided into different phases with different goals that are to be achieved. The first step of the project was to conduct a literature review and to research the selected CC technologies. The main goal of this first step was to obtain the specific energy data and other relevant information for the different CC technologies. The second step began with performing the necessary calculations in order to obtain the energy requirements. During the second step, a mapping of the mills energy system was conducted with the main focus being the steam network. From this, the goal was to find energy integration opportunities and investigate how implementation of CC for CO_2 utilization in a lignin extraction unit would affect the energy system of the mill. With the knowledge obtained from the first two steps, an techno-economic assessment and qualitative assessment of the suitability of the technologies was conducted in order to find advantages and disadvantages of the different CC technologies with the goal of providing an overall evaluation from the findings during the project. A schematic overview of the work procedure is provided in Figure 4.1 and a more detailed description is provided throughout this chapter.

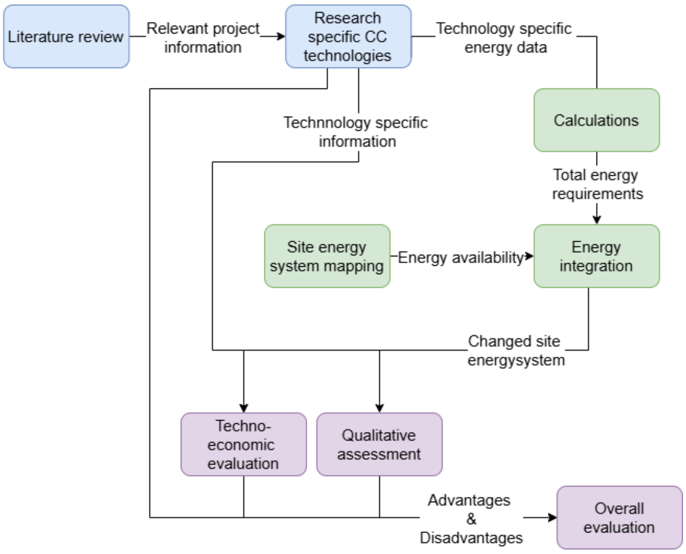


Figure 4.1: A schematic overview of the procedure to achieve the objectives of the project.

4.1 Energy requirement and assumptions

The initial phase of this project consisted of a literature review with the aim of acquiring the necessary knowledge about the pulping process, lignin extraction process and the different CC technologies of interest. Through this review, the necessary data for the energy requirements of CC technologies for capturing 20 kton of CO_2 per year were gathered. The energy requirements for the investigated CC technologies are summarized in Table 4.1 and the different assumptions and sources are later presented in detail.

Table 4.1: Technology comparison for CO_2 capture methods excluding cooling of flue gases and compression of product CO_2.

Technology	Energy demand	Boundary conditions	Technology Specifications
MEA	Heating demand: 3.36 MJ/kg CO_2 Cooling demand: 1.55 MJ/kg CO_2 Electricity demand: 0.0157 MJ/kg CO_2	Inlet temperature: 40°C Outlet pressure: 1.95 bar	Capture rate: 90% Solvent makeup: 3.1 kg/t CO_2
HPC	Heating demand: 1.28 MJ/kg CO_2 Cooling Demand: 3.16 MJ/kg CO_2 Electricity demand: 0.35 MJ/kg CO_2	Inlet temperature: 25°C Outlet pressure: 1.3 bar	Capture rate: 90% Solvent makeup: 0.31 kg/t CO_2
Membrane	No heating demand Cooling demand 0.67 MJ/kg CO_2 Electricity demand: 0.7 MJ/kg CO_2	Operating temperature: 40°C Outlet pressure: 1 bar	Capture rate: 70% Membrane life time: 5-10 years Membrane area: 2515 m^2
Solid adsorption	Steam demand: 1.9 kg/kg CO_2 Cooling demand: 3.5 MJ/kg CO_2 Electricity demand: 0.34 MJ/kg CO_2	Inlet temperature: 40°C Outlet pressure: 1 bar	Capture rate: 90-95% Sorbent life time: 3-5 years

When extracting data from the literature, it was considered that the energy requirement for CC depends on several factors. This was addressed by reviewing studies with similar capture specifications to this project, primarily focusing on inlet flue gas composition and product purity. However, the scale of the plant was assumed not to affect the energy requirement on a per-mass CO_2 basis. The specific energy demands that are presented in Table 4.1 excludes the cooling demand for obtaining the required flue gas inlet temperature along with electricity demand for compression and compressor cooling of the product stream to the desired conditions for the lignin extraction facility. Furthermore, all data found in literature was not directly applicable to this project and needed to be either calculated based on given conditions or changed based on assumptions as explained below.

Using absorption based CC with MEA is, as mentioned in Section 2.2.1.1, one of the most well known and well studied technologies in the field. Thus the aim was to find a study with similar flue gas conditions as this project in order to find appropriate data regarding energy consumption of CC [37]. The make-up requirement for MEA was obtained from [38].

For the HPC process, none of the energy demand values were directly obtained from literature. Instead, the data originates from a fully electric HPC system operating at a flue gas CO_2 concentration matching this project's conditions [39]. This setup was then adapted to represent a partially heat-driven process. The reevaluation was carried out using an energy balance based on the electricity required to generate the necessary steam [40]. The heat demand could thus be estimated, and the corresponding electricity consumption was subtracted from the total energy electricity demand for CC. The cooling demand was then calculated under the assumption that the product CO_2 exits the top of the stripper saturated with steam. The make-up need is assumed to be 10% of that for MEA, based on the relative solvent degradation rates presented in [41].

The CC process using selective membranes was seen to be heavily dependent on inlet flue gas CO_2-concentration. Consequently, particular emphasis was put on finding a data source for the energy requirement which was derived for similar flue gas conditions as in the case for this project [16]. The cooling demand however, was not possible to extract from the cooling demand associated with CC using membrane technology, hence a simple Aspen model was assembled to estimate the cooling demand driven by compressor cooling throughout the CC process, as can be seen in Appendix A.

The evaluation of the solid adsorption technology in this work was limited by the availability of detailed data, requiring several assumptions to be made. The source used for estimating steam and electricity demands was based on different operating conditions — specifically, a lower CO_2 concentration in the flue gas and a significantly larger plant size [34]. The total electricity demand provided in the source also included energy for product compression and liquefaction, which are not considered in this study. Therefore, the electricity demand was re-evaluated by subtracting the energy contributions for product compression and liquefaction using estimates from

[42]. Additionally, because of the lower CO_2 concentration in the literature, the remaining energy demand was adjusted proportionally based on the inlet flue gas flow rate. The cooling demand for the solid adsorption system was not explicitly specified in the literature and was therefore estimated as a theoretical maximum. The calculation was based on the assumption that only steam and carbon dioxide exit the regeneration stage. Additionally, it was assumed that the steam adsorbed by the bed material replaces the carbon dioxide on a one-to-one molar basis.

The energy required for capturing the necessary CO_2 for the lignin extraction plant can be divided into different categories as listed below.

- Energy demand for cooling the flue gases to the inlet temperature of the CC plant.
- Energy demand for the CC plant including heating, cooling and electricity.
- Energy demand for condensing water vapor in the product stream to achieve the required conditions for the CO_2 product stream.
- Energy demand for compression and cooling of the product gas to the desired conditions for the lignin extraction plant.

As can be seen in Table 4.1, the different CC plants have different boundary conditions and different technology specifications that will change the required energy for CC. In order for the CC plant to function as specified, the flue gases needs to be cooled to the inlet temperature of the CC plant. The flue gases entering the cooling unit will have composition and temperature according to Table 3.2 and 3.3.

The energy penalty for the technologies is numerically evaluated based on loss in electricity production and cooling demand. The loss in electricity depends both on the electricity used within the CC unit and the loss of electricity production due to steam being used to supply heat for CC instead of electricity production. Further loss in electricity due to CC is the compression of CO_2 after the CC unit. This electricity demand depends on the outlet conditions of the CC unit which can be seen in Table 4.1. The cooling demand is evaluated as thermal output which disregards the temperature of the required cooling water.

4.2 Energy Integration

Based on the description in Section 3.2 the heat demand for the different CC technologies will be provided by using excess steam from the recovery boiler that would otherwise be used for power generation in the condensing turbine. This can be achieved by increasing the load of turbines G3 or G5, depending on which steam pressure and temperature are required. When the load of the back pressure turbines is increased, there will be less steam available for the condensing turbine and hence lower electricity production. However, the turbines have a maximum capacity at which they can operate and during some hours of the year, it is predicted that the turbines will operate at maximum load. During these hours, it is not possible to further increase the load of the back pressure turbines to meet the heat demand of the CC plant. Thus, bypassing the turbines is required to supply steam to the CC system at the appropriate temperature and pressure. On the other hand, when there is no excess steam from the recovery boiler, the load of the back pressure turbines cannot be increased simply by shifting steam flow from the condensing turbines. At such operating conditions, the steam demand can be met by increasing the steam production from the power boiler at the mill. During the major part of the project, the assumption has been that there will be steam available to decrease the load of the condensing turbine and available capacity to increase the load of the back pressure turbines. This means that for the economic evaluation, the price of using steam is equal to the price of electricity that could have been produced with that steam. There is also one investigated scenario where the steam price is estimated based on the cost of producing steam in the power boiler with externally bought fuel to calculate the cost of CC when extra steam is required.

For all of the studied CC technologies, the flue gas needs to be cooled to the specific inlet temperatures as given in Table 4.1. The cooling demand for the flue gas to inlet temperature of the CC plants is met using a direct contact cooler (DCC). The DCC unit will not only provide the cooling demand but also provides further cleaning of the flue gases. With the DCC however, there is no possibility for heat integration and the cooling demand for this step will be met with cooling towers.

4.2.1 MEA

A CC plant using MEA requires heating, cooling and electricity. The heating demand for this capture technology is the reboiler duty for the regeneration of solvent. In the reboiler, the generated steam is at a pressure of 2 bar and a temperature of 130 °C. This means that the heat demand can be provided by low-pressure (LP) steam from the ÅL3 header. Thus the load of the G5 turbine is increased to satisfy the increased steam demand on the ÅL3 header while the load of the condensing turbine is decreased. The cooling demand for the technology is located at three different parts of the CC system as can be seen in Figure 4.2.

Firstly there will be a cooling requirement for the flue gas that exits the lignin dryer before entering the CC plant so that the flue gases will have correct temperature for the plant to operate as specified. Secondly, cooling is required for the recycled solvent before entering the absorption column. For the technology to operate optimally the streams entering the absorption column should have a temperature of 40 °C. Finally, a condenser is required to remove steam from the product stream at the top of the stripper. Some of the cooling demand for CC will be at temperatures that would make it possible to produce hot water that can be utilized in the mill. Regarding the electricity demand for absorption-based CC using MEA, there is only a small demand to operate pumps within the CC plant and an electricity demand for compression of the CO_2-product stream.

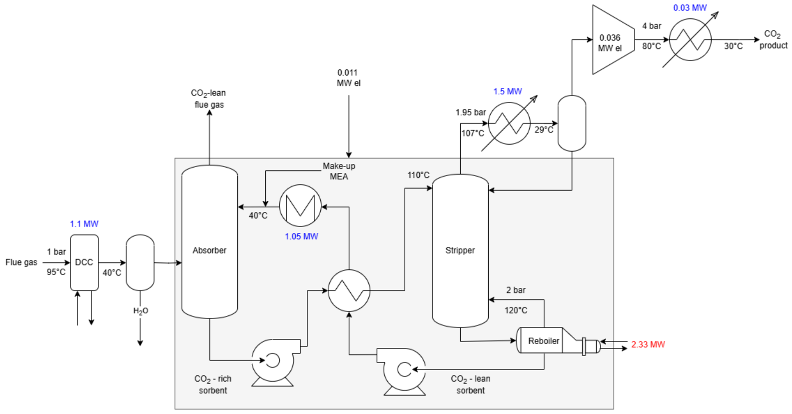


Figure 4.2: Description of the MEA system with cooling demands given in blue, heat demand in red and the electricity demand within the boundaries of the CC plant.

4.2.2 HPC

Similar to the case of CC using MEA, the HPC technology also requires heating, cooling and electricity. However, by using HPC the heating demand is reduced and the electricity demand is increased. The regeneration of solvent for this technology also utilizes a reboiler, but with steam generation at a pressure of 1.31 bar and temperature of 135°C. Since the ÅL3 steam keeps a temperature of approximately 155 °C this is sufficient to supply the required temperature and heat demand. The extra steam demand in the ÅL3 header can be supplied through increased load of the G5 turbine and thus decrease the load of the condensing turbine. The gas leaving from the top of the stripper is at a temperature of about 100°C and is saturated with steam. Some stages of the condensation process will reach a temperature suitable for heat recovery, enabling heating of process water in the mill's secondary heating system. A description of the system, along with the corresponding energy duties, is shown in Figure 4.3.

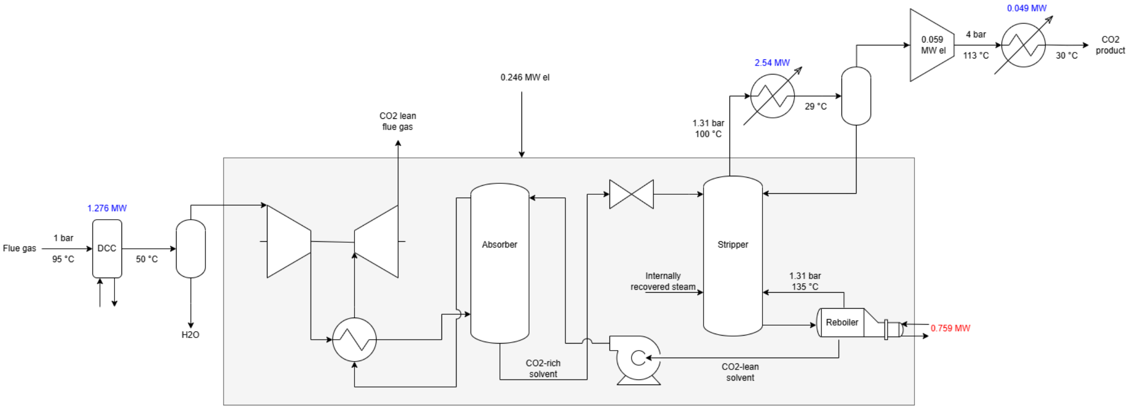


Figure 4.3: Description of the HPC system with cooling demands given in blue and heat demand in red, along with the system electricity demand.

4.2.3 Membrane

If selective membrane gas separation is implemented for CC, there will be no steam demand associated with CC. There is however cooling demands at several different stages during the CC process as can be seen in Figure 4.4. Firstly there is the DCC unit after the lignin dryer that removes much of the water vapor and other impurities in the flue gas stream. Then the gas is compressed which increases the temperature of the gas and thus the gas needs to be cooled to the membrane inlet temperature. This cooling demand will be through indirect cooling and thus there will be a possibility for heat integration with the secondary heating system. This will also be possible with the cooling demand after the second compression stage before the second membrane. After the membrane CC the product stream will need to be pressurized before entering the lignin extraction unit which will, similarly to the other technologies, decrease the excess electricity availability at the mill.

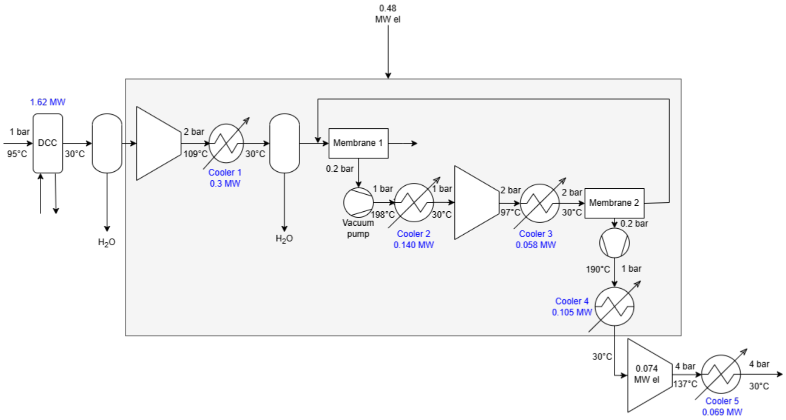


Figure 4.4: Description of the membrane system with cooling demands given in blue, along with the system electricity demand.

4.2.4 Solid adsorption

In solid adsorption CC, the primary driver for sorbent regeneration is a concentration swing rather than a temperature swing. However, steam is still utilized in the regeneration process, as described in Section 2.2.3. The steam required for the CC process must be at a pressure of 1 bar and 120°C. Currently, there is no steam extractions from the turbines at this pressure level hence the steam needs to be throttled to reach the specified conditions. If steam from the ÅL3 header is throttled to 1 bar, it will be at a too high temperature and hence it can be mixed with water from the secondary heating system to reach appropriate conditions. Additionally, as seen in Figure 4.5, hot air is used in the conditioning step, which creates a heating demand. This heating demand is, to the best of our understanding, already included in the steam demand in Table 4.1 as the steam used for sorbent regeneration also can be used for heating of conditioning air. The cooling demand for this technology comes from cooling the flue gas to 50 °C with a DCC and from the condensation of steam to separate it from the end product. The gas that exits the regeneration step has a temperature of 120 °C which means that the cooling and condensation of the end product can be integrated with the secondary heating system. The electricity demand provided in Table 4.1 includes the power needed to rotate the beds and for fans in the CC unit. There will also be, similar to the other CC processes, compression of flue gas to the desired pressure of 4 bar which will result in a reduction of excess electricity at the mill.

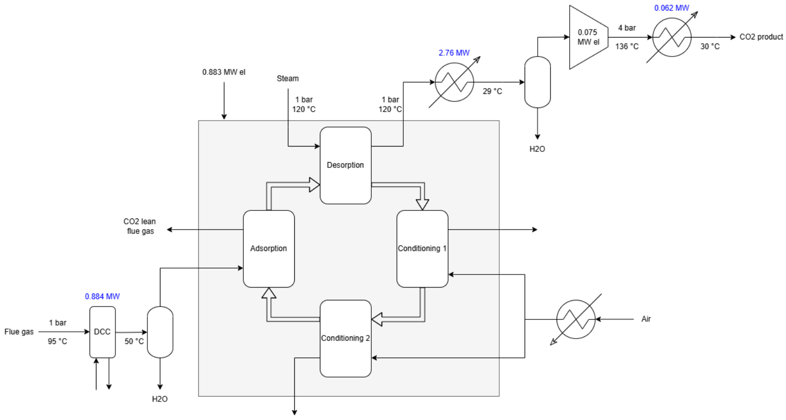


Figure 4.5: Description of the solid adsorption system with cooling demands given in blue, along with the system electricity demand.

4.3 Economic evaluation

The CO_2 demand for the lignin extraction plant will initially be delivered from externals suppliers. The main reason for implementing on-site CO_2 capture is to reduce the cost of obtaining CO_2 for utilization in the lignin extraction unit. This means that the total cost for CO_2 capture (operational cost and investment cost) needs to be lower than the cost of externally supplied CO_2. The investment costs for the different technologies are difficult to evaluate based on published literature, especially for less commercial technologies like solid adsorption. The estimation of investment cost becomes even more difficult due to the small scale considered for the CC plant. Due to the uncertainties in the investment cost, this project used the investment opportunity to obtain the maximum investment cost while remaining profitable. The investment opportunity was calculated with Equation 4.1, which is dependent on the operational expenses (OPEX) compared to an external supplier of CO_2.

$$Investment\,opportunity = (OPEX - C_{\mathrm{CO_2}})\frac{1-(1+i)^{-n}}{i} \tag{4.1}$$

In the equation $C_{\mathrm{CO_2}}$ represent the cost of external supplied CO_2 which includes the cost of liquid CO_2 and transportation of CO_2 to the mill site with prices according to Table 4.2. Furthermore, in Equation 4.1, i represents the discount rate and n plant life time. The OPEX consists of four different parts: make-up of solvent, membranes or adsorption modules, electricity consumption, loss of electricity production and cooling water. Estimations of investment costs for the different CC technologies were also derived but will be highly uncertain. The life time of the investment project was assumed to be 25 years with a discount rate of 10%. Table 4.2 provides the required data for the economic evaluation [43][44][45][46][47].

Table 4.2: Data required for economic evaluation.

Electricity	50 EUR/MWh
Liquid CO_2	192 EUR/t CO_2
CO_2 transportation	72 EUR/t CO_2
Cooling	15 EUR/(kW·year)
Biomass	33 EUR/MWh

Regarding the cost calculations related to make-up material, Table 4.3 provides prices for the different materials considered [48][49][16][50].

Table 4.3: Economic data required for make-up cost calculations.

MEA solvent	2 EUR/kg solvent
HPC solvent	1.35 EUR/kg solvent
Membrane material	68 EUR/m^2 membrane
Adsorption sorbent	26 EUR/kg

The make-up costs for MEA and HPC were directly calculated based on make-up requirements from Table 4.1 and solvent costs from Table 4.3.

When selective membranes are used for capturing the required CO_2, the membranes will need to be regularly replaced to ensure a high quality product. The membrane replacement was thus counted as a make-up cost for this technology. The make-up cost was calculated based on the membrane price per square meter and the required membrane area for the CO_2 capture, along with a 5 years lifetime of the membrane as can be found in Table 4.1. The lifetime of the membranes can be used to estimate how much membrane material that needs to be replaced every year which can be seen as an operational cost in Equation 4.1.

For solid adsorption, the make-up cost arises from the replacement of the adsorption modules. This cost includes not only the material cost of the sorbent (CalF-20) but also the cost of the module itself. The evaluation was based on cost estimates from a direct air capture (DAC) unit which, although using a different sorbent material, employs a similar modular filter design [51]. To adapt the DAC-based estimate, the investment cost was adjusted for differences in material costs. Additionally, due to the significant difference in CO_2 concentrations between air and flue gas, the cost was scaled based on the sorbent's CO_2 adsorption capacity at relevant concentrations [52]. Finally, the cost was scaled to the appropriate plant size, and the lifetime of the modules was then used to evaluate how many modules needed to be replaced every year. The replacement of modules could then be seen as an operational cost and was used accordingly in Equation 4.1.

The investment cost was difficult to predict due to the many influencing factors and the limited availability of detailed economic data. However, it remains an important component in the overall evaluation of the different technologies. In this project, the investment costs were estimated based on data from previous publications and adjusted using scaling factors. The scaling factor adjusts for the non-linear relationship between plant capacity and cost. It reflects economies of scale, the idea that larger units have lower specific cost for capturing CO_2. The scale factor α can be used according to Equation 4.2

$$Cost_1 = Cost_2 \left(\frac{Size_1}{Size_2} \right)^{\alpha} \tag{4.2}$$

where $Cost_1$ represents the estimated cost for the scale of $Size_1$, $Cost_2$ is the cost from previous publication with the corresponding plant size of $Size_2$. The scaling factors applied to the various technologies are presented in Table 4.4 [53]. These factors were based on the degree of modularity of each system. For example, membrane and solid adsorption technologies are considered highly modular due to their use of membrane or filter modules. In contrast, absorption-based technologies involve fewer modular components, such as large absorption and desorption columns, resulting in lower scaling factors. The CAPEX was also scaled to current prices using the chemical engineering plant cost index (CEPCI). As shown in the table, the HPC process used a slightly lower scaling factor than MEA. This is due to additional complexity, such as the inclusion of compressors, turbines, and high-pressure operation.

Table 4.4: Estimated scale factors for the different CC technologies used for investment cost calculation.

Technology	MEA	HPC	Membrane CC material	Membrane major equipment	Solid adsorption
Scaling factor	0.7	0.6	0.9	0.5	0.8

The uncertainties in the scaling factors vary, partly due to limited published data and partly because of differences in the commercial maturity of the technologies. To account for this, a sensitivity analysis was performed by varying the scaling factors. MEA and membrane material are associated with the highest level of certainty — MEA due to the large amount of published data, and membranes because of their highly modular nature. Consequently, their scaling factors were varied by ± 0.05 in the analysis. In the sensitivity analysis, the scaling factor for the membrane major equipment was kept constant due to the high certainty of the compressor scaling factor. In contrast, HPC and solid adsorption systems are less certain. For HPC, the uncertainty is linked to the operational complexity associated with increased pressure, while for solid adsorption, the limited commercial deployment contributes to the uncertainty. Therefore, for these technologies, the sensitivity analysis was conducted by varying the scaling factors by ±0.1.

5

Results

This chapter presents the results of the techno-economic evaluation conducted in this study. The results are structured to first address the energy demand associated with the different CC technologies, followed by the corresponding economic outcomes. Firstly, the energy requirements, including electricity, heating, and cooling demands, as well as the potential for heat recovery. The economic results are then presented, where different operational scenarios are evaluated, such as increased capture capacity, implementation of maximum heat recovery, and operation without available steam. A sensitivity analysis is then provided, examining the impact of key uncertainties on the economic performance of the CC systems. Lastly, a qualitative assessment of the different technologies, considering practical and operational factors beyond quantitative results.

5.1 Energy Demand

This section presents the results related to energy demand, including net electricity loss, which accounts for both the electricity requirement for CC and the decreased electricity production from the usage of steam. Additionally, the section details the cooling requirements for each technology and highlights the potential for heat recovery

5.1.1 Electricity and heating demand

Figure 5.1 illustrates the net electricity loss associated with implementing different CC technologies. The figure also presents the various contributions to the total electricity loss. As shown, using solid adsorption results in the greatest electricity loss, driven both by the system's own electricity consumption and the lost electricity production from using steam. In contrast, HPC has the lowest overall electricity loss, mainly due to the limited usage of steam compared to MEA and solid adsorption while presenting low electricity demand compared to membrane separation.

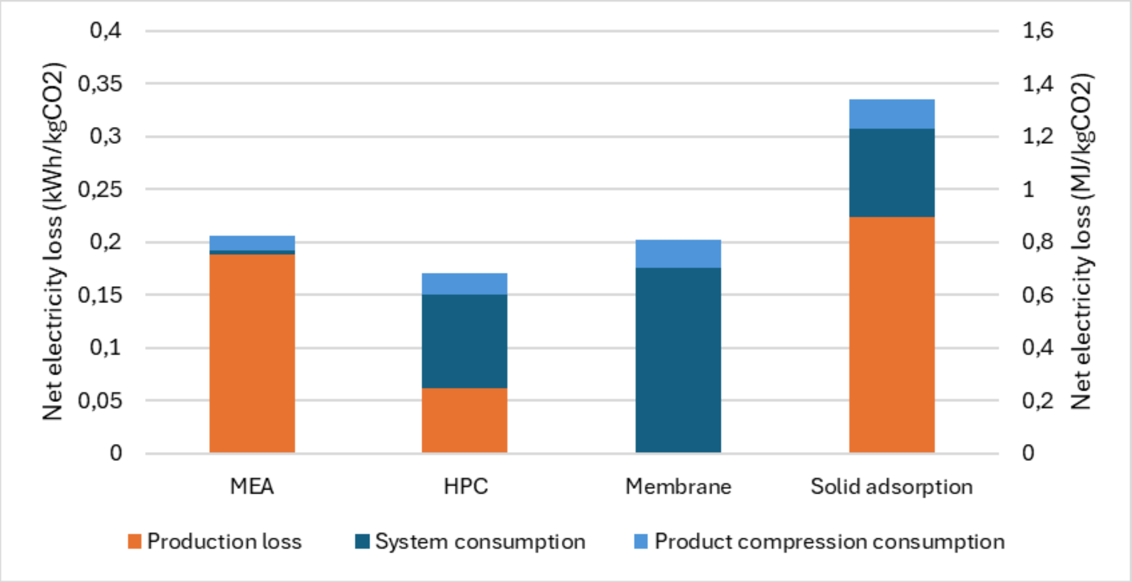


Figure 5.1: Net electricity loss associated with the different CC technologies.

Table 5.1 presents the steam demand for the different technologies in terms of mass flow, along with the corresponding loss in electricity production. The table also includes the electricity consumption, covering both system operation and product compression, followed by the total net electricity loss.

Table 5.1: Summary of energy requirements that contribute to the electricity losses.

	MEA	HPC	Membrane	Solid adsorption
Steam demand from ÅL3 (kg/s)	1.09	0.356	-	1.3
Production loss (MW)	0.524	0.170	-	0.620
Electricity consumption (MW)	0.047	0.305	0.561	0.309
Net electricity loss (MW)	0.571	0.475	0.561	0.929

5.1.2 Cooling demand

All of the CC technologies require cooling, although to varying degrees, as illustrated in Figure 5.2. The largest consumers of cooling are the DCC and the condenser. This is primarily because these units not only reduce the temperature of the gas streams but also remove water through condensation, which is an energy intensive process.

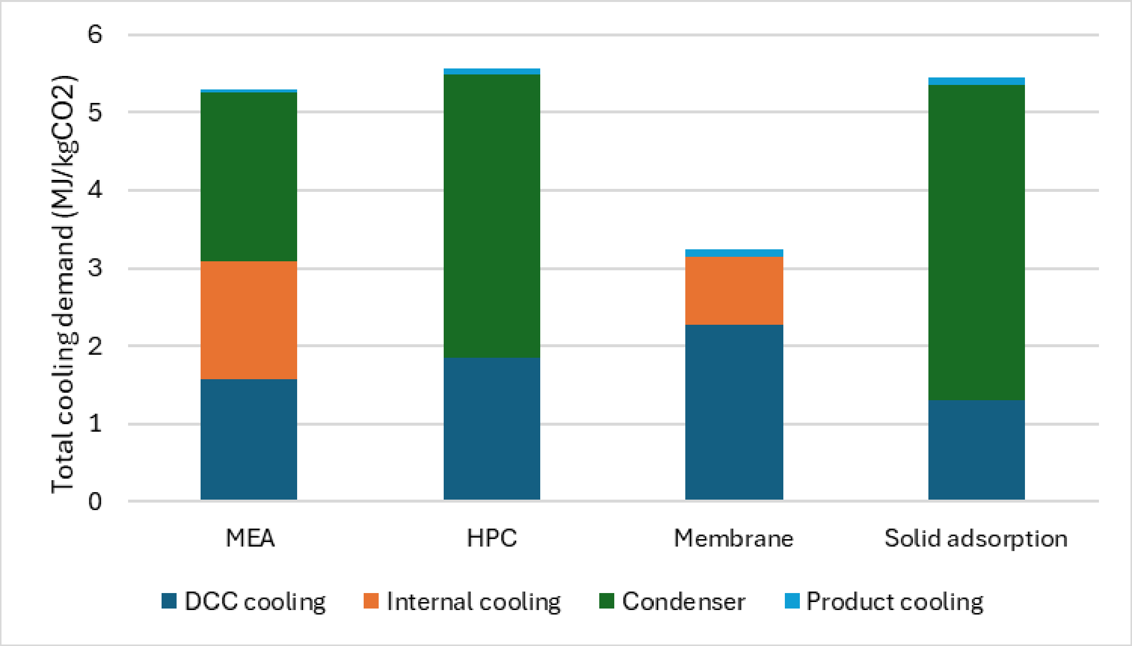
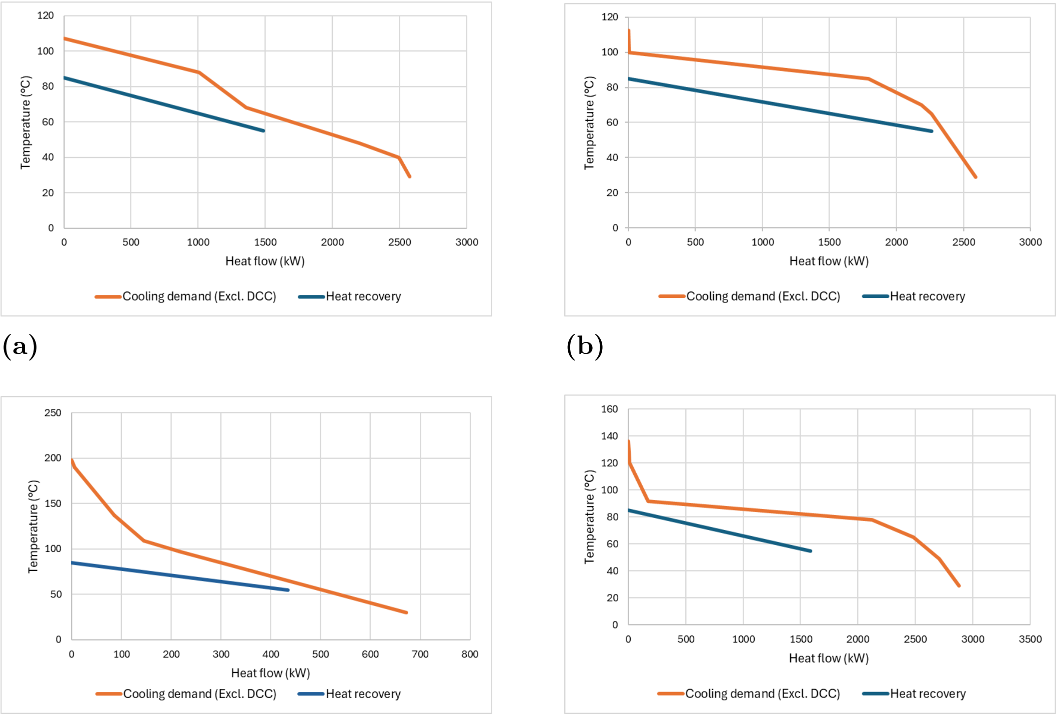


Figure 5.2: Summary of cooling contribution for the different CC technologies.

5.1.3 Heat recovery

This section presents the results from analysis of heat recovery opportunities. In Figure 5.3, the hot composite curves for the capture processes are shown, illustrating the total cooling demand of the hot streams at various temperature levels, excluding the DCC. The figures also illustrate the maximum amount of heat that can be recovered as hot water using excess warm water from the secondary heating system. For the heat recovery, it is assumed that warm process water at 55°C is heated to a temperature of 85°C. It is worth noting that the membrane technology includes multiple small coolers, which makes practical implementation of heat recovery more challenging and expensive. In contrast, for the other technologies, the majority of the cooling demand originates from the condenser, which operates mostly at temperatures above 85°C. Heat recovery from these condensers is therefore more favorable and requires a lower investment cost per unit of heat recovered.



(a)

(b)

(c)

(d)

Figure 5.3: Hot composite curves and heat recovery potential for (a) MEA, (b) HPC, (c) Membrane, (d) Solid adsorption.

From Figure 5.3, it can also be seen that there is potential for further heat recovery if lower grade heat is desired. However as there is currently a surplus of warm process water at the mill and hence it is not of interest of further heat recovery.

5.2 Economic results

This section presents the results of the economic evaluation. Figure 5.4 shows the operational expenditures (OPEX) for the different technologies. The OPEX includes: (1) cooling costs when heat recovery is not implemented, (2) make-up costs, which cover replacement of degraded solvent in MEA and HPC, membrane replacement after its specified lifetime, and replacement of adsorption filters in the solid adsorption system, (3) electricity costs from the system's operational power demand and CO_2 product compression, and (4) steam costs, which represent the opportunity cost of lost electricity production when steam is diverted for use in the capture process.

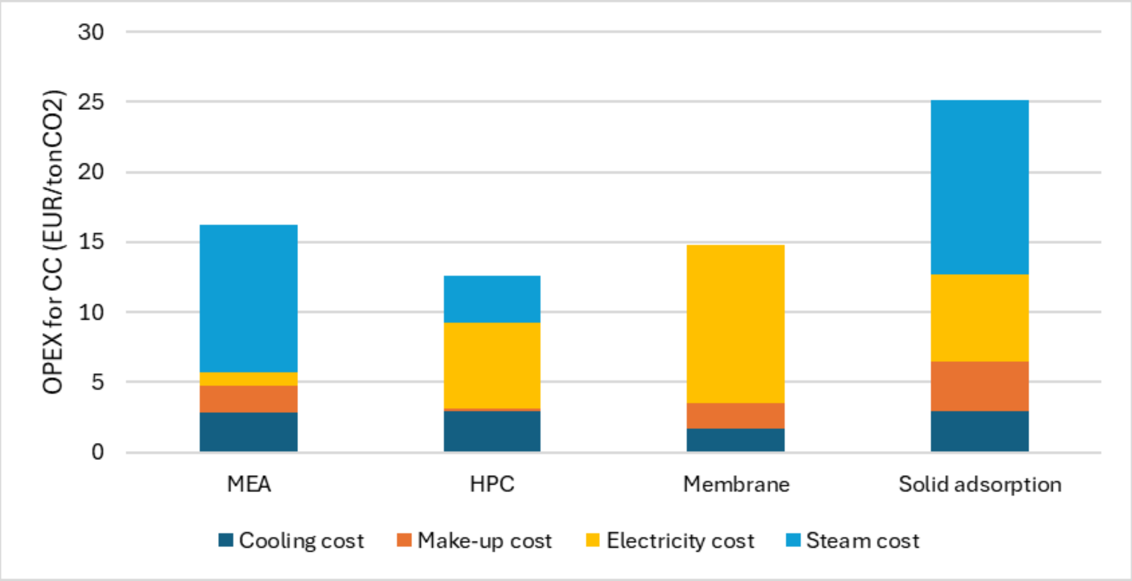


Figure 5.4: Summary of OPEX for the different CC technologies.

Table 5.2 presents the OPEX for the different CC technologies, along with the annual cost of purchasing CO_2 from the market. The purchase cost includes both the price of liquid CO_2 itself and transportation expenses. Liquefaction of CO_2 is not required for on site CC since it is utilized as gas in the lignin extraction plant. Among the evaluated technologies, solid adsorption has the highest OPEX; however, it still amounts to only 9.5% of the cost of buying CO_2. For the other technologies, the OPEX as a percentage of the CO_2 purchase cost is 6.1% for MEA, 5.1% for membrane, and 4.8% for HPC. Table 5.2 also shows the resulting investment opportunity for the different technologies.

Table 5.2: Comparison of OPEX and investment opportunity across the different CC technologies.

Technology	OPEX (kEUR/yr)	Investment opportunity (MEUR)
MEA	324	55.2
HPC	252	56.0
Membrane	296	55.6
Solid adsorption	502	53.3
Purchase CO_2	5 280	–

Figure 5.5 presents the investment opportunity alongside the estimated investment costs for the different technologies. The investment cost estimates are based on previous publications and have been scaled using the scaling factors provided in Table 4.4 and converted to present prices using CEPCI. As shown in the figure, the margin between the investment opportunity and the investment cost is substantial, even for HPC, which has the highest investment cost. However, these results are associated with significant uncertainty. Firstly, the investment opportunity is based on the current CO_2 price, which may fluctuate, and on the OPEX values calculated in this thesis, where several assumptions have been made. Secondly, the investment cost estimations are based on data that do not perfectly match the case conditions and have been adjusted using scaling factors. Despite these uncertainties, the margins between the investment opportunity and investment cost are large enough to accommodate potential variations while still maintaining project profitability.

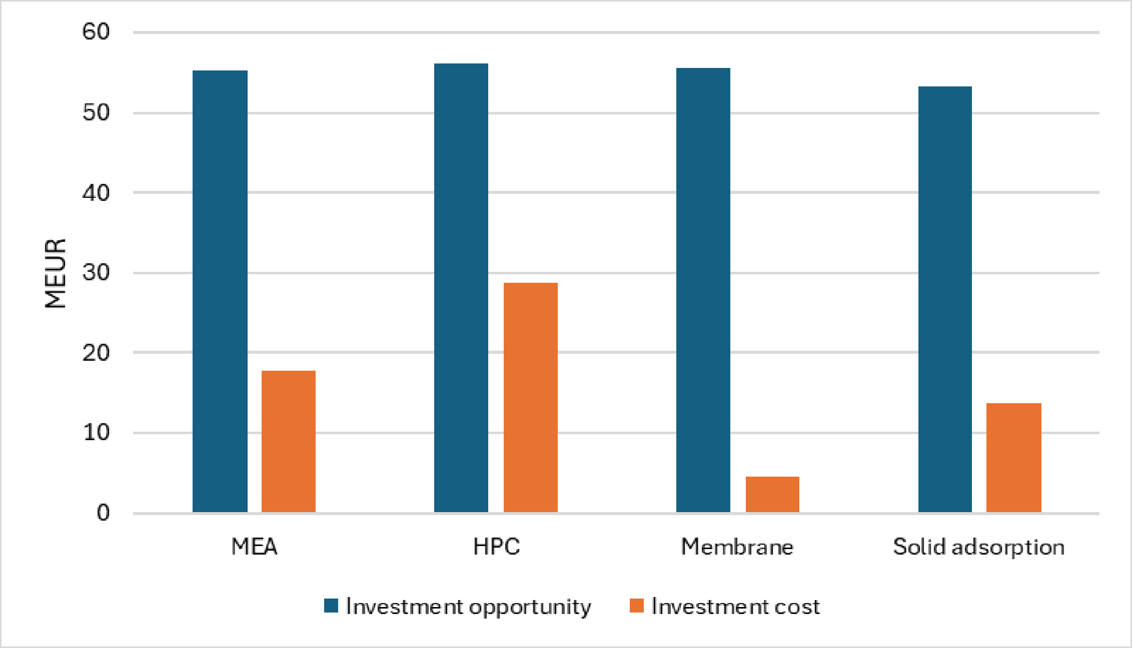
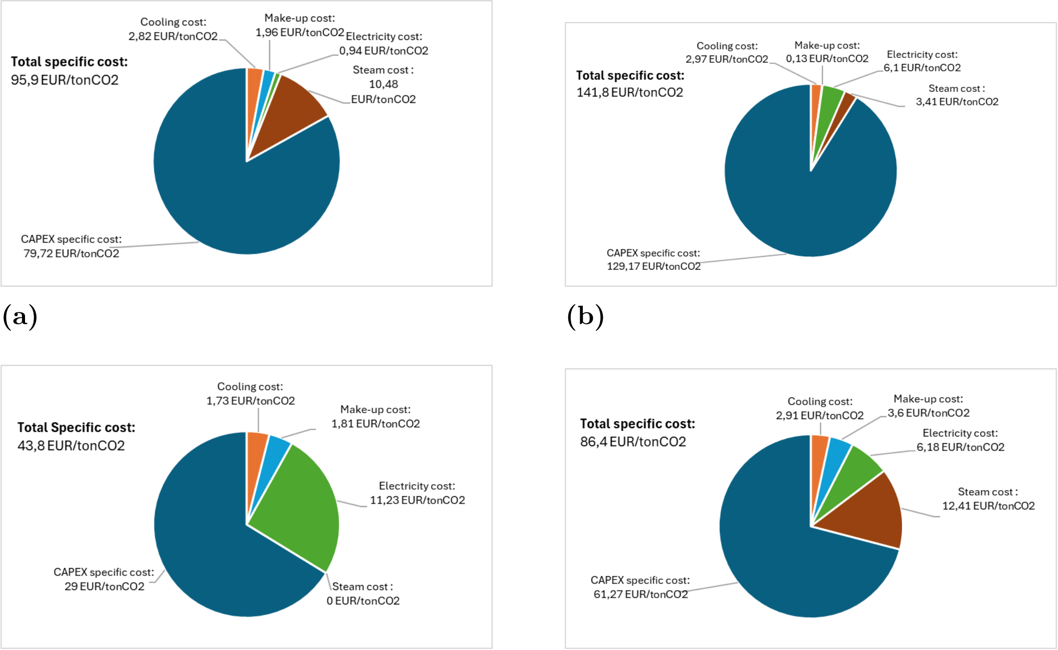


Figure 5.5: Investment opportunity compared to estimated investment costs for the different CC technologies.

The scaled investment costs were also annualized to estimate the corresponding specific costs. In Figure 5.6, the breakdown of specific cost contributions is presented, clearly illustrating that the investment cost constitutes the largest portion of the total expense for all CC technologies.



(a) **(b)**

(c) **(d)**

Figure 5.6: Specific cost contribution for (a) MEA, (b) HPC, (c) Membrane, (d) Solid adsorption.

5.2.1 Scenario with increased capture capacity

In this section, the economic impact of increasing the capture capacity is evaluated. The flue gas from lime kiln 1 contains approximately 170 kton/yr of CO_2, which sets the upper limit for potential capture. However, since the membrane technology considered in this study achieves a capture rate of only 70%, the economic assessment is based on capturing 120 kton/yr of CO_2. In Table 5.3, the specific costs are presented. When comparing this table with Figure 5.6, a clear reduction in specific cost can be observed for all technologies. Additionally, Figure 5.7 presents the investment opportunity alongside the estimated investment costs for the increased capacity scenario, illustrating the improved economic feasibility at higher capture capacities. The specific price for externally bought CO_2 could potentially also decrease with higher quantities, but this has not been taken into consideration in this case.

Table 5.3: Performance of different technologies under the increased capacity scenario, showing the specific cost.

Technology	Specific cost with increased capacity (EUR/tonCO_2)
MEA	62.8
HPC	75.7
Membrane	32.4
Solid adsorption	67.9

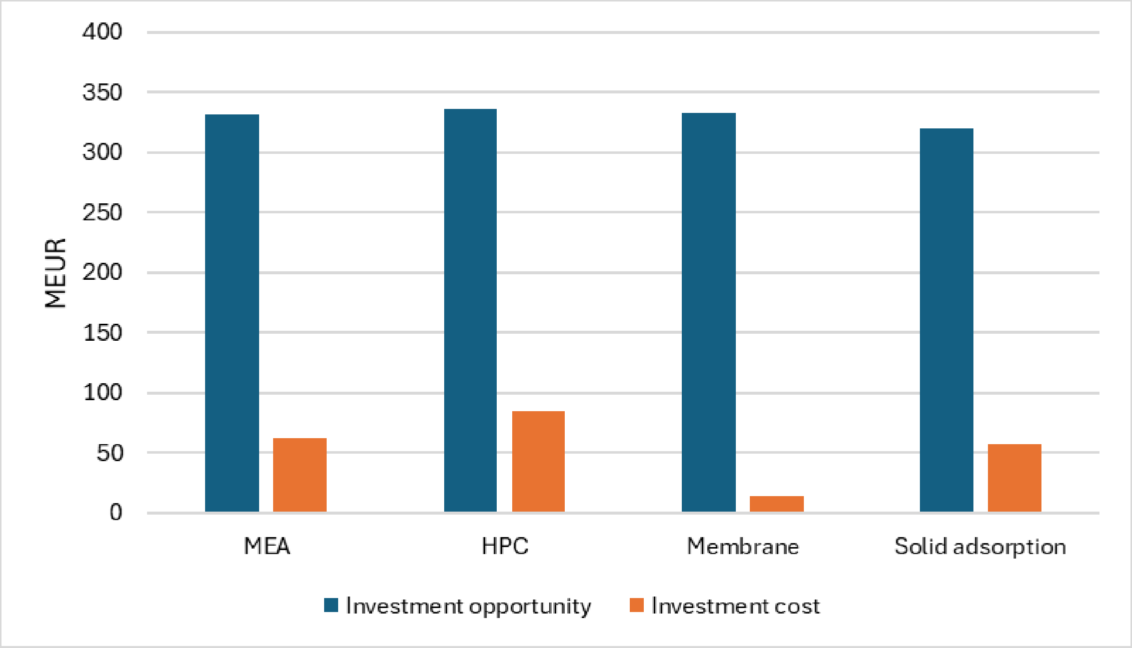


Figure 5.7: Investment opportunity compared to estimated investment costs for the different carbon capture technologies under the increased capacity scenario.

5.2.2 Scenario with maximum heat recovery

As presented in Section 5.1.3, there are opportunities to recover heat from the capture processes to the mill's secondary heating system. This influences the operational cost in two ways: partly by reducing cooling costs and partly by supplying heat to the secondary heating system. If it is assumed that the recovered heat can be used to produce hot water, and that hot water could replace consumption of LP steam from the ÅL3 header, or would otherwise be produced using such LP steam, the value of the recovered heat is directly correlated to the value of LP steam. This value can be derived assuming that a reduction in LP steam demand enables HP steam to be redirected to the condensing turbine for increased electricity production. The resulting reduction in cooling costs and the increased income from additional electricity generation can be seen in Figure 5.8 as a negative OPEX for CC. The demands from the original scenario are also presented in the figure together with the predicted OPEX that could be achieved with maximum heat recovery. It can be observed that the greatest benefit is achieved for HPC, which follows from the high heat recovery potential, as discussed in Section 5.1.3. The percentage decrease in OPEX for the different technologies can be seen in Table 5.4. It should be noted that implementation of heat recovery would also affect the investment cost (leading to higher costs for heat exchangers), but this has not been considered within the scope of this work.

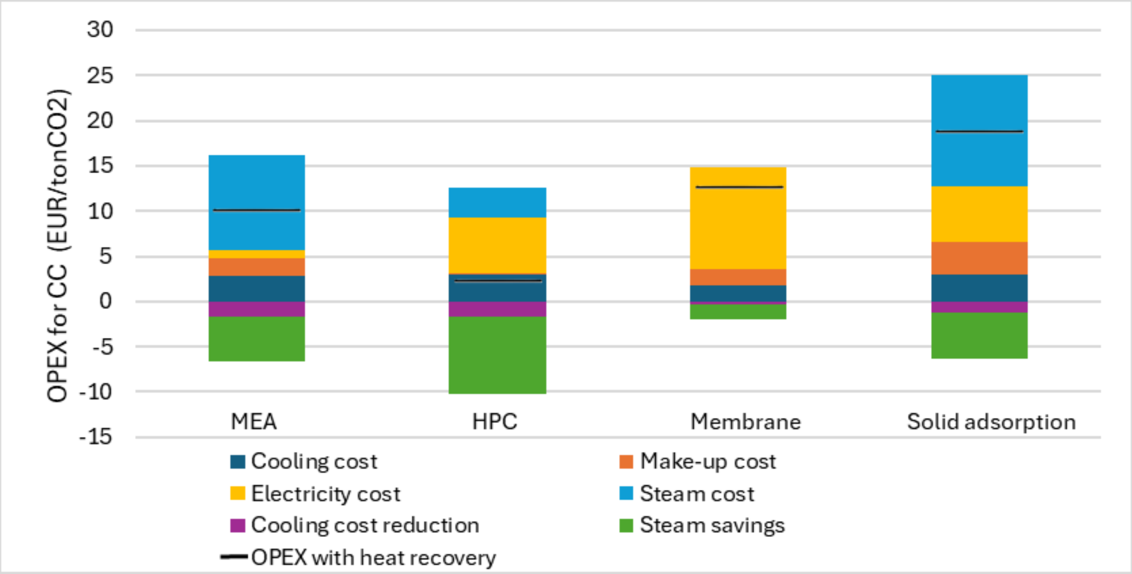


Figure 5.8: Summary of operational cost for CC and cost reduction potential with heat recovery.

Table 5.4: Percentage decrease in OPEX with implementation of maximum heat recovery.

Technology	Decreased OPEX (%)
MEA	37.4
HPC	80.7
Membrane	13.4
Solid adsorption	25.1

5.2.3 Scenario with no available steam

In the above sections, the assumption has been that there will be steam available to satisfy the demand for CC by redirecting steam from the condensing turbine. Since the extraction of lignin from black liquor will limit the steam availability at the mill there will likely be hours where the turbine G6 will not be in operation. It will thus not be possible to satisfy the steam demand for CC by decreasing the load of the condensing turbine and increasing the load of a back pressure turbine to increase available steam at the ÅL3 header. During these hours, the steam demand for CC can be supplied using the power boiler at the mill. This will affect the OPEX for

CC since steam becomes more expensive. The cost of using LP steam for the two different scenarios can be seen in Table 5.5.

Table 5.5: Cost of steam when either rebalancing the turbines (redistributing steam from the condensing turbine) or supplying additional steam from the power boiler with externally bought fuel.

Option	Cost (EUR/ton steam)
Rebalance turbines	6.7
Additional steam production from power boiler	19.5

The OPEX for the scenario as a result of fuel bought externally for the power boiler to satisfy the steam demand is illustrated in Figure 5.9 (and can be compared with Figure 5.4 where steam demand was satisfied by turbine rebalancing).

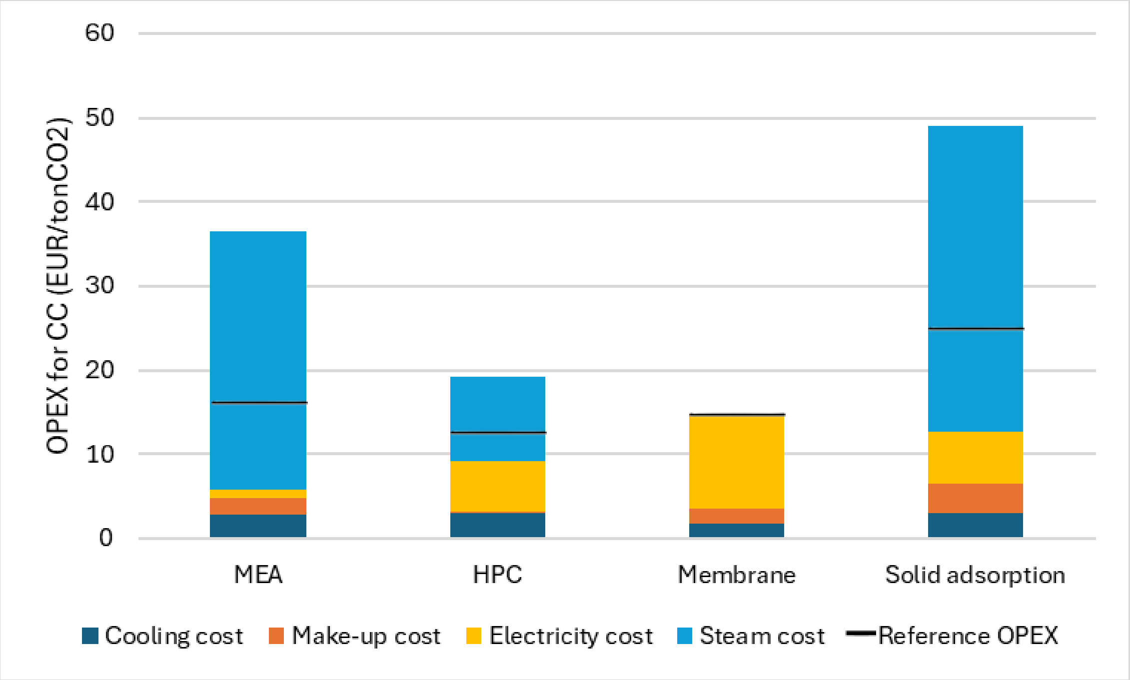


Figure 5.9: Summary of OPEX for the different CC technologies when steam is produced by the power boiler with externally bought fuel.

Furthermore, Table 5.6 presents the percentage increase in OPEX for the different technologies when the steam demand is provided from the power boiler with externally bought fuel.

Technology	Increased OPEX (%)
MEA	124.8
HPC	52.2
Membrane	0
Solid adsorption	95.4

Table 5.6: Percentage increase in OPEX when steam is supplied from the power boiler with externally bought fuel.

It can thus be seen that when there is requirement for steam production with power boiler, CC becomes more expensive (except for membrane). It has to be noticed though, that the results from Figure 5.9 and Table 5.6 do not say anything about the total cost for capturing the required CO_2 but just the specific cost for the duration when steam is produced in the power boiler with externally bought fuel. In order to see the effect on the total cost, there is a requirement for a more extensive analysis of the steam availability after implementation of lignin extraction to see what duration of the year this will be the case.

5.3 Sensitivity analysis

With such small scale CC compared to the sizes for which investment costs are reported in literature, the investment costs estimated in this work are particularly uncertain. When plant sizes are scaled by orders of magnitude, the investment cost can become heavily dependent on the scaling factor that is used, hence a sensitivity analysis was conducted and the results are shown in Table 5.7.

Table 5.7: Sensitivity analysis of specific CAPEX and cost for the different CC technologies with different scale factors.

Technology	Scaling factor	Specific CAPEX (Euro/tonCO_2)	Specific cost (Euro/tonCO_2
MEA	0.65	94.5	110.7
	0.7	79.7	95.9
	0.75	67.2	83.5
HPC	0.5	186.8	199.4
	0.6	129.2	141.8
	0.7	89.3	101.9
Membrane	0.85	31.6	46.4
	0.9	29	43.8
	0.95	26.8	41.6
Solid adsorption	0.7	94.3	119.4
	0.8	61.3	86.4
	0.9	39.8	64.9

As seen in Table 5.7, the selection of scale factor will heavily influence specific

CAPEX for CC. This is because, as earlier explained, the reference plant sizes are orders of magnitude larger than for this project and hence the scale factor will heavily change the investment cost estimation. Because of this, the specific cost for carbon capture will also be highly influenced as can also be seen in Table 5.7.

The CO_2 market remains quite uncertain, both due to the growing interest in CC and ongoing questions surrounding CO_2 storage. Consequently, it is likely that the price of CO_2 will fluctuate in the coming years. To address this uncertainty, a sensitivity analysis was performed, evaluating the investment opportunity at varying CO_2 prices to see the investment margins. The results of this analysis are presented in Table 5.8. As shown in the table, even with a 50% variation in CO_2 price, the investment cost (seen in Figure 5.5) remains below the investment opportunity for all technologies, with membrane and solid adsorption technologies maintaining a particularly favorable margin. Furthermore, with all technologies except HPC, there can also be further major uncertainties in the investment cost estimation while still keeping the investment profitable.

Table 5.8: Sensitivity analysis of investment opportunity for the different CC technologies with different CO_2 prices.

Technology	CO_2 price (Euro/tonCO_2)	Investment opportunity (MEUR)	Relation between investment opportunity and investment cost (%)
MEA	90	33.8	52.5
	180	55.2	32.2
	270	76.6	23.2
HPC	90	34.6	83.1
	180	55.6	51.4
	270	77.0	37.2
Membrane	90	34.2	13.3
	180	55.6	8.2
	270	77.0	5.9
Solid adsorption	90	31.9	42.9
	180	53.3	25.6
	270	74.7	18.3

5.4 Qualitative assessment

During the project, a qualitative assessment was conducted to get an overview of advantages and disadvantages of the different CC technologies that were deemed as relevant for the considered CC implementation. The following section presents the qualitative results from the literature review and summarizes the advantages and disadvantages of each technology in Table 5.9.

Table 5.9: Qualitative comparison of the different CC technologies.

Technology	Advantages	Disadvantages
MEA [21] [22] [4]	Low dependency on electricity. Lower complexity than HPC for easier retrofit possibility Well established technology TRL of 9	Health concerns related to solvent degradation. Sensitive to impurities such as NO_x, SO_x an particles Other amine based solvents can outperform MEA
HPC [54] [25] [4]	Low toxicity Low tendency for solvent degradation	Potential corrosive acid formation from flue gas compression TRL of 7-8
Membrane [16] [4] [26]	Not related to health concerning substances Modularity making it easy to scale Not dependent on steam availability	Sensitive to impurities such as NO_x, SO_x and particles Sensitive to feed CO_2 concentration Membrane life time of 5-10 years TRL of 6-8
Solid adsorption [55] [56] [4]	Low waste generation and easy disposal of spent sorbent Easy setup, startup, load following, operation and shutdown No significant health, environmental or safety risk	Uncertainties in impurity resistance Filter life time of 3-5 years TRL of 7

6

Discussion

In this chapter, the results that were obtained for this master's thesis are discussed. First, the data availability and underlying assumptions are discussed to clarify the uncertainties within the study. This is followed by a discussion regarding the energy requirements and integration opportunities, and then a discussion of the economic results. The discussion then shifts to plant compatibility to better assess the practical application potential of the studied technologies. Finally, alternative solutions to satisfy the CO_2 demand for the lignin extraction plant are considered.

6.1 Data availability and Assumptions

One major uncertainty in this work lies in the technology data that has been collected. The goal has been to find data for process designs that meet specific requirements such as flue gas CO_2 concentration, product purity, and capture rate. However, due to limitations in publicly available data, it has not always been possible to meet these requirements across all technologies. For example, the data for solid adsorption was sourced from a case with a lower flue gas CO_2 concentration than in this study, which required assumptions to be made regarding its impact. This may have resulted in an overestimation of the energy requirement since lower CO_2 concentration often correlates to higher energy demand for CC. Moreover, while these parameters were the main focus for consistency, other factors also vary between the technologies such as the scale at which they were evaluated and differences in flue gas composition beyond just CO_2. The various publications used were also produced by different authors, each with limited insight into all their assumptions and strategies. Another source of uncertainty stems from the way the technology specifications were established; for example, membrane performance is based on simulation results and solid adsorption on projected performance of an upcoming plant.

The uncertainty in the data decreases as the commercial maturity of the technologies increases. For technologies that are further away from commercialization, both the availability of relevant data and the certainty of the data tend to be poorer. MEA and HPC are the most commercialized technologies among those considered in this study, and therefore the literature data used for these cases aligned best with the conditions of this project. For membranes, even though the aim was to find data for systems similar to this case, the more limited publications for this technology resulted in some deviations, for example, slightly lower CO_2 concentration. The largest deviations were associated with solid adsorption, where multiple assumptions had to be made. For instance, the available data included significant energy use for compression and liquefaction, which had to be excluded from the total energy demand using estimates from other sources.

During the majority of this project, it was assumed that the steam demand for the different CC technologies could be supplied by utilizing steam that would otherwise pass through the condensing turbine. This would be the cheapest way to meet the steam demand for CC, but it requires that there is sufficient capacity available in the mill's back-pressure turbines and steam available in the condensing turbine to accommodate the resulting redistribution of steam flow. However, steam availability can vary due to several factors, including seasonal fluctuations and whether it is hardwood or softwood campaign. In situations where the available steam production is insufficient to meet the CC demand, the power boiler at the mill must be used to supply additional steam, which leads to a higher cost for the steam utilized in the CC process. As shown in Figure 5.9, this scenario significantly impacts MEA and solid adsorption technologies, as both are highly dependent on steam for the capture process. The operational cost for HPC is also affected, although to a lesser extent, since it relies less heavily on steam. In contrast, CC using selective membranes remains unaffected in these circumstances, as it does not require steam for CC.

6.2 Energy Requirement and Integration

All of the CC technologies studied in this thesis require different types and amounts of energy, as was shown in Section 5.1. It has been seen that for such small scale CC there will be a very low steam mass flow requirement to satisfy the demand. This steam demand can either be met by redistributing steam flow in the turbines to increase the available steam in ÅL3 steam header or by increased steam production from the power boiler at the mill. The major difference between these options is that the steam supply with turbine steam redistribution becomes cost efficient since the only cost of using this steam is the loss in relatively low-efficiency electricity generation while the cost of steam from the power boiler can become rather high since fuel might have to be bought externally. With the implementation of a lignin extraction unit at the mill there will be less steam available and it is thus likely that there will be more and longer periods when utilization of the power boiler is required. Since the membrane CC technology does not require steam, or any other heat source, it becomes independent of the steam availability at the mill.

Furthermore, all the studied CC technologies require some form of cooling. The flue gas must be cooled to a specific temperature before entering the CC plant, which creates a need for flue gas cooling and consequently, flue gas condensation. To meet this demand, a DCC was employed, which also serves the added purpose of further cleaning of the flue gases. As illustrated in Figure 5.2, one notable advantage of membrane technology is its comparatively low cooling demand. This is largely due to the absence of steam condensation in the CO_2 product stream, as membranes do not rely on steam in the separation process. This reduces the overall cooling requirement, offering a potential operational benefit over the other technologies studied.

However, when considering heat recovery in Section 5.1.3 the potential for membrane-based capture is significantly lower than the other technologies. The reason for the lower heat recovery potential is partly because of the absence of a condenser, which is the most significant part of the heat recovery potential at higher temperature level for the other cases. It should also be noted that the DCC makes the flue gas cooling inappropriate for heat recovery and was thus not included in the integration analysis. The balanced composite curves in Figure 5.3 illustrate that all CC technologies provide possibilities for heat integration for heating of process water. It was assumed that hot process water could be further utilized at the mill and thus LP steam could be saved that would otherwise be used for water preheating. Hence, some of the energy that is being used for CC can be recovered and utilized. However, for solid adsorption, the pinch point occurs at a higher temperature than for the other technologies. As a result, its heat recovery potential could be significantly improved if the target temperature for the hot water were lowered.

6.3 Economics

The economic results from this master's thesis can be interpreted in several ways, with the preferred technology shifting depending on which aspect of the results is emphasized. When focusing on the operating costs (see Figure 5.4), it is evident that solid adsorption have the highest operating cost among the options considered. However, examining the investment cost relative to the investment opportunity (see Figure 5.5) it reveals that the investment costs for HPC and MEA require the largest share of their respective investment opportunities. This indicates that although solid adsorption technology perform worse in terms of operational costs, they offer a better potential economic margin compared to purchasing CO2 when investment cost is included.

The significance of the investment cost is further illustrated in Figure 5.6, which presents a breakdown of the total specific costs for each technology. It illustrates that CAPEX accounts for over 90% of the total specific cost for HPC, and over 80% for MEA, while for membrane and solid adsorption, it is around 60-70%. These results highlight that the primary expense for all technologies arises from the investment costs. This outcome is partly a consequence of the small-scale CC application considered in this study, as specific investment costs tend to increase more significantly at reduced scales, particularly for HPC and MEA.

Additionally, in Table 5.3, the specific costs for an increased CC capacity scenario are presented. When comparing these results with the original scenario (Figure 5.6), it is clear that the specific costs decrease more rapidly for HPC and MEA than for membrane and solid adsorption, further reinforcing how scale influences the economic performance of the different technologies.

By implementing heat recovery, OPEX can be reduced through both cooling cost savings and decreased steam consumption, as presented in Figure 5.8. However, as shown in the figure, the extent of cost savings varies between technologies, with HPC achieving the greatest benefit. It is important to note, though, that implementing heat recovery would require additional investments in heat exchangers and supporting equipment, costs that have not been considered within the scope of this project.

Furthermore, the results presented only reflect the theoretical maximum potential for heat recovery, which may not represent the preferable option from an economic perspective. For example, in the case of the membrane technology, the cooling demand is distributed across five smaller cooling units, as illustrated in Figure 4.4. Achieving maximum heat recovery in this case would require five additional heat exchangers, which could prove cost-inefficient, particularly given the relatively modest reduction in operating costs.

As presented in Figure 5.2, both MEA, HPC, and solid adsorption have a high cooling demand for the product condenser with high amounts of latent heat at an appropriate temperature for heat recovery. Thus, by implementing just one extra heat exchanger, there is potential for great heat recovery. It is thus of interest to further evaluate the potential for heat recovery when investment cost is included to find the economic feasibility.

The economic calculations presented in this thesis carry significant uncertainties, partly because they rely on the current plant conditions and available market prices, which may be inaccurate or subject to changes in the future. As shown in Figure 5.9, fluctuations in steam costs have a substantial impact on OPEX, particularly for MEA and solid adsorption technologies, while membrane technology remains unaffected. In this case, operational costs greatly increase for some technologies, showing the sensitivity of the results. However, the scenario depicted in Figure 5.9 is unlikely to occur for more than a few days per year. Another perspective is provided by the sensitivity analyses presented in Section 5.3, where variations in both scaling factors and CO_2 prices were examined. The results show that the economic performance of membrane technology remains robust across these variations, while HPC proves to be the most sensitive in both cases. This resilience can be attributed to the membrane system's primary reliance on electricity and relatively low investment cost, making it less susceptible to changes in scaling assumptions or CO_2 market prices. It is important to note however, that variations in electricity prices were not tested in this study. Such changes would likely have a significant impact on membrane-based systems. Nevertheless, since the steam cost in this study is also directly proportional to the electricity price, both will fluctuate similarly, reducing the risk of a drastic shift in the economic balance between technologies in the event of electricity price changes alone.

6.4 Plant Compatibility

In Table 5.9, the advantages and disadvantages of the different technologies are presented. One particularly important aspect highlighted is the systems' resistance to impurities such as SOx, NOx, and particles. As shown, MEA is sensitive to these components, while solid adsorption technologies are reported to have good resistance. Based on the data in Section 3.4 and Table 3.3, it can be concluded that the flue gas contains no detectable SOx. The NOx content, on the other hand, is relatively high, though it consists primarily of NO and negligible amounts of NO_2, which is typically the more problematic nitrogen oxide for amine-based systems. It is important to note, however, that the exact composition of the flue gas after the DCC is currently unknown. The particle content is similarly uncertain, but it is expected to change as a result of the lignin drying process. Additionally, the DCC is anticipated to remove a portion of the particles prior to the flue gas entering the CC system. Given these considerations, it is reasonable to assume that the flue gas will be relatively clean upon reaching the CC plant, suggesting that all investigated technologies should be technically compatible in this regard. Nevertheless, strong resistance to potential contaminants remains a favorable property, providing operational flexibility and increased robustness under varying process conditions.

The technologies also differ in terms of toxicity and environmental impact. MEA is the most concerning in this regard, as it involves the use of amines, which pose health risks to personnel during handling. The other technologies studied during this project however, do not share these concerns. From an environmental standpoint, solid adsorption uses materials with no significant environmental effect and allows for relatively easy disposal of spent sorbents. Membrane systems also offer advantages, such as a long operational lifetime, resulting in lower waste generation which is favorable both from an environmental perspective but also from the perspective of maintenance with longer intervals between membrane replacement.

Availability of cooling and heating is another important aspect to evaluate the compatibility of the different technologies. The supply of cooling water at the mill is supplied through cooling towers and the capacity is thus limited. This means that the cost of cooling could be increased if investments in additional cooling capacity are required. However, with the implementation of the lignin extraction facility, there will be decreased steam production and less steam available for the condensing turbine resulting in decreased cooling demand. This cooling capacity could then possibly be used for CC. It is still worth considering that if cooling capacity availability is deemed to be a limiting factor, a CC technology with lower cooling demand, such as membrane, can be favorable. This could be even more important if there is interest for further expansion of on-site CC beyond the usage for lignin extraction where investment in extra cooling capacity or further effort for heat integration could be required.

Furthermore, considering the reduction in specific capture cost with increased plant capacity, especially for HPC, it could be beneficial to investigate the potential for investing in a plant with higher capacity and run the capture plant at partial load to limit OPEX. This can become an interesting option if there is future interest of capturing increased amounts of CO_2, for example, to increase lignin extraction capacity, capture CO_2 for permanent storage or enter the market with biogenic CO_2. If there is an interest for future expansion of the capture plant without the option of initially investing over-capacity, the membrane technology with its modular characteristics becomes increasingly attractive. Investing in membrane CC with the capacity required for the planned lignin extraction plant will not increase the specific cost of CC compared to the other technologies. Thus future expansions become easier since there will only be a requirement for extra membrane modules and no major increase in specific capture cost. However, It is mostly the membrane modules with the membrane material that scales linearly with capacity and hence it might be of interest to invest in larger compressor and pump capacity even for membrane CC since these components does not scale linearly with capacity.

6.5 Alternative Solutions to Satisfy the Carbon Dioxide Demand

Even though small-scale CC appears to be a promising alternative to purchasing CO_2 from the market, other potential solutions not explicitly addressed in this master's thesis could be considered. One such scenario involves a future increase in the supply of CO_2 on the market as interest in CC grows. This could decrease the price of CO_2, potentially making some of the CC technologies evaluated in this thesis less cost-effective. In such a case, continuing to purchase CO_2 from the market might remain the simpler and more economical option. However, as discussed and presented in Section 5.3, even with a 50% reduction in CO_2 price, the investment opportunity still exceeds the investment cost with a good margin for all technologies except HPC, which shows a smaller margin. Naturally, there are limits to this resilience, and if the CO_2 price were to fall by an additional 50%, producing CO_2 on-site would become questionable for technologies like MEA, HPC, and solid adsorption, making market-purchased CO_2 a much more relevant and competitive alternative. It is also worth to mention that if the price of CO_2 would decrease with 50%, it would probably be because CC becomes much cheaper and would hence decrease the cost of on-site CC as well which has not been taken into consideration in this study.

It was also established during the initial phase of the project that only post-combustion CC technologies were to be investigated. Still, some well-known CC technologies have been left out of this master's thesis for different reasons that could still theoretically be possible to implement. One of the more established CC technologies that would have been conceptually different to the ones investigated in this project would be cryogenic CC. Cryogenic CC was not investigated since the main advantages of this technology is that it delivers a highly pure product as liquid. This requires lots of energy for liquefaction of CO_2, which is beneficial if the CO_2 should be transported to permanent storage, but not necessary for the purpose of lignin extraction. Another possibility for CC would be using a chilled ammonia process. This technology was not further investigated since it has a similar working principle as the other absorption processes and due to time limitations, it was decided that two absorption-based CC technologies would be sufficient for the purpose of this master's thesis. If decided that absorption-based capture would be the most suitable approach, other solvents than MEA and HPC should be investigated.

7

Conclusion

The aim of this thesis was to evaluate the potential for on-site CC for utilization of CO_2 in a lignin extraction unit at Södra Cell Mönsterås. Four different CC technologies, namely two absorption-based with MEA and HPC solvent, membrane and solid adsorption were investigated and evaluated based on their energy requirement, capture cost and other relevant aspects for capturing 20 kton CO_2/year. The different CC technologies presented different energy requirements with solid adsorption resulting in the highest combination between electricity consumption and decreased electricity production from the steam consumption. Solid adsorption also presented the highest OPEX of about 25 EUR/ton CO_2 while HPC resulted in lowest OPEX of about 13 EUR/ton CO_2. With implementation of maximum heat recovery with hot process water, HPC process will give the lowest OPEX of 2.4 EUR/ton CO_2 due to the high amounts of heat that can be recovered.

With the investigated small scale for the capture plant the investment cost becomes uncertain due to the lack of projects and publications about CC at this scale along with the high dependency of the scaling factor. Hence, an investment opportunity was calculated which is the difference between the cost of externally supplied CO_2 and the OPEX for CC, representing the maximum investment cost for economic viability. This enables a comparison where it can be seen how close the estimated investment cost is to the investment opportunity. With the uncertainties regarding investment cost, it can differ significantly from the base case estimation as was seen during the sensitivity analysis. However, even though there are uncertainties in the investment cost for the different technologies they all show great potential for low-cost CO_2 supply compared to utilizing externally supplied CO_2 for lignin extraction. The only exception is the HPC process where the margin between investment cost and investment opportunity becomes small if the CO_2 can be purchased at prices around 90 EUR/ton. Thus the CC technologies with more modular design, such as membrane and solid adsorption, seem to be more suitable options for small scale CC even though it would mean a slightly higher OPEX for CC.

Further advantages that favor membrane and solid adsorption is that they are not related to health concerning substances and are constantly under development to become more resistance to degradation and to achieve longer lifetime. The lower TRL for these technologies might, however, impose doubts. Nevertheless, with the current amount of research in the field of CC and the decision to initially meet the

CO_2 demand through external suppliers, there will be time for the technologies to become more mature.

In conclusion, this thesis identifies membrane technology as having the greatest potential for small-scale CC, due to its low specific capture cost, modularity, and independence from steam availability. However, it is also concluded that significant uncertainties remain within the results, and that all the evaluated technologies hold the potential to offer a cost competitive supply of CO_2 to varying degrees.

This study serves as an initial investigation into the implementation of small-scale CC and should not be regarded as providing exact results, due to the many uncertainties involved. However, these uncertainties have been acknowledged, and their potential impact has been discussed in order to present transparent results.

7.1 Future Work

There are still several areas for further investigation for on-site small scale CCU. This includes more detailed investigation of the steam availability at the mill in Mönsterås after the implementation of the lignin extraction plant. Additionally, the effect of electricity price variations could be implemented in future work to gain a better understanding of the technologies' sensitivity to potential market changes. Also, if it is of interest to invest in a capture plant with higher capacity, the possibility to run the plant at partial load to still have low OPEX but with the potential of increased capture rate in the future needs to be explored.

There are also more possible options for future work connected to the heat recovery. To enhance the economic evaluation when heat recovery is implemented, the investment cost of heat exchangers and piping, which would increase the overall capture cost, should be estimated. Further investigation should also be conducted regarding the availability of cooling capacity, as this study has assumed that sufficient cooling infrastructure is already in place on-site. If additional cooling capacity is required, it could potentially lead to increased investment costs, for example through the installation of new cooling towers.

Furthermore, in order to make the results more accurate, simulations should be performed with the specific conditions of the flue gases after the lignin dryer, preferably obtained from measurements when the lignin extraction plant is constructed, and more specific data from CC technology suppliers should be acquired. This will also make it possible to look at for example specific membranes to get more accurate performance indication, or to test different solvents for absorption to potentially decrease energy requirement and solvent degradation.

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A

Aspen Model for Membrane Carbon Capture

The Cooling demand for membrane carbon capture was not found in literature and hence a simple aspen model was assembled to estimate the cooling demand. The membranes was not simulated but instead component splitters where used to obtain the correct flow rates and concentrations according to literature. The aspen model is shown in Figure A.1.

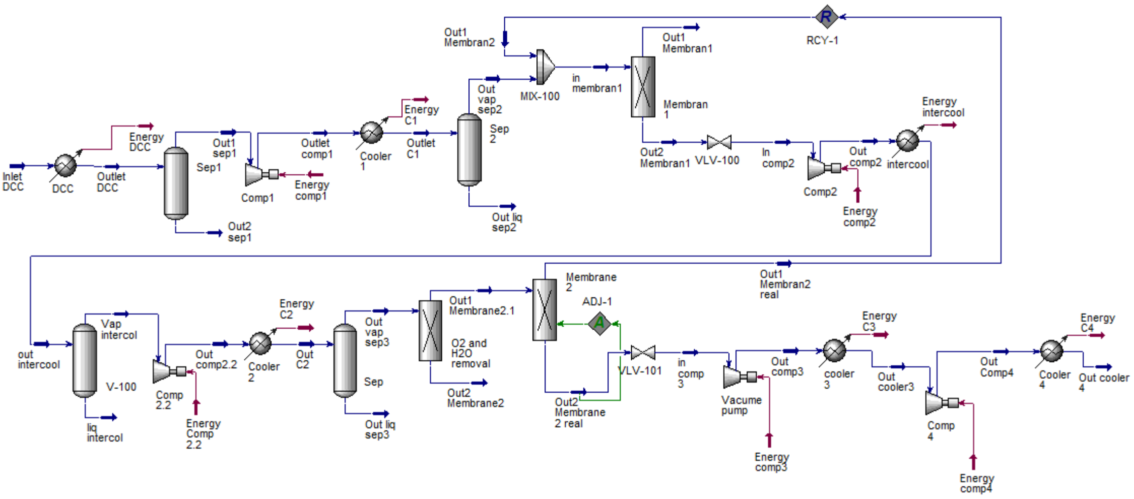

Figure A.1: Aspen model for simulating membrane separation

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