ACCSESS

Providing access to cost-efficient, replicable, safe and flexible CCUS

Advanced capture configurations for selected pulp and paper plants incl. techno-economic analysis

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Coordinated by: SINTEF Energi AS - www.sintef.no/energy

About ACCSESS

If CO_2 capture and storage (CCS) is to become a relevant, large-scale technology for cutting carbon dioxide (CO_2) emissions, several barriers need to be addressed, and its deployment must be accelerated.

ACCSESS works to address key challenges to the successful implementation of CCS across Europe: namely, challenges related to CO_2 capture, CCS chains, and societal acceptance. The project focuses on four industrial sectors with the potential to drastically reduce CO_2 emissions by implementing CCS: waste-to-energy, pulp and paper, cement, and biorefineries.

ACCSESS started in May 2021. Its consortium consists of 18 partners from eight different European countries.

www.projectaccsess.eu

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Abstract

This report presents estimations of CO_2 capture and avoidance costs for advanced CO_2 capture integration configurations in pulp and paper mills. The report is a deliverable from work package 5 of the ACCSESS project, where focus has been on Stora Enso's kraft pulp mill located in Skutskär (Sweden) and Stora Enso's recycled paper mill located in Langerbrugge (Belgium). The capture technologies considered for pulp and paper mill integration are post-combustion capture technologies using an amine-based solvent (AMP/PZ) and a carbonate-based solvent (CO2 Solutions).

In the Pulp Mill, heat integration opportunities for both capture technologies were evaluated using pinch-analysis tools. The results indicate that the high-temperature excess heat from the recovery boilers is sufficient to meet the heat demand for capture. However, without additional fuel use, integrating carbon capture in this way would result in a loss in electricity generation. Similarly, in the Paper Mill, it was found that the heat demand for capturing CO_2 could only be met by steam extraction from one of the turbines, with a resulting loss in electricity generation.

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Comparing the capture cost between the Paper Mill and Pulp Mill confirmed that site-specific factors, such as CO_2 flow, concentration of CO_2 in the flue gases and the geographical location of the mill, have a strong influence on the capture cost.

Avoiding losses in electricity generation in the Pulp Mill by firing additional fuel for steam generation was explored, leading to the development of several heat integration scenarios. This was done by optimizing the size of a simplified steam cycle to maximize electricity generation either using existing back-pressure steam turbine capacity or investing in extended capacity. Additionally, as pulp mills in the future may look different from today due to strategic developments towards better biomass resource utilization, the cost of CO_2 capture in a Pulp Mill with lignin extraction was also evaluated. This cost was found to be higher than for the Pulp Mill without lignin extraction, which clearly indicates that the cost of carbon capture implementation is benefitted by favourable mill energy balances.

A sensitivity analysis assessed the impact of future energy market uncertainties on the capture cost of the heat integration scenarios of the Pulp Mill. At low electricity prices, the results indicate that capture cost does not differ significantly if fuel consumption or co-generation of electricity is prioritized. In a high electricity price market, on the other hand, investing in extended back-pressure steam turbine capacity, and therefore producing more electricity than the Pulp Mill without carbon capture, clearly achieves the lowest capture cost.

The reboiler heat demand of the CO_2 Solutions™ process can be covered by recovering excess process heat due to its lower regeneration temperature. In the Paper Mill, there is limited potential for heat recovery, however in the Pulp Mill, it was found that approximately 34% of the heat demand for capture could, theoretically, be met by excess heat from the mill instead of by low-pressure utility steam. Comparing the capture cost of the CO2 Solutions™ process between the two sites indicate that excess heat availability is an important parameter for achieving a lower capture cost. Of the excess heat potential identified for the Pulp Mill, a single process stream of black liquor flash steam provides 25% of the heat requirement for capture. For the AMP/PZ process, the possibility of upgrading the black liquor flash steam using a mechanical-vapor recompression (MVR) heat pump to meet part of its heat demand was explored where it was found that the potential cost savings from reduced LP utility steam compensate quite well the cost of investing in and operating an MVR heat pump with a limited temperature lift.

A bottom-up cost engineering approach was adopted to estimate the CAPEX of the capture technologies where "Nth-of-kind" (NOAK) cost factors were utilized, following the assumption that the retrofit will occur in the future, when carbon capture integration with the pulp and paper industry has reached a greater level of maturity. As carbon capture has yet to be demonstrated in the pulp and paper industry, the NOAK cost estimates presented in this work are optimistic compared to expected cost of near-term implementation and should be treated as such.

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1 INTRODUCTION

With large point sources of biogenic CO_2 emissions at relatively high concentration (13-20%), the pulp and paper industry, notably kraft pulp mills, has a large potential for achieving carbon dioxide removal (CDR). One of the most mature methods available to achieve technological CDR is biogenic carbon capture and storage (Bio-CCS). Based on point sources in Europe above 0.1 Mt in 2018, it was estimated that the potential for Bio-CCS is 62 (±5) Mt/a (Rosa et al., 2021). For reference, all pathways that limit global warming to 1.5°C, with limited or no overshoot, feature Bio-CCS deployment of up to 1000, 8000, and 16 000 $MtCO_2$ per year in 2030, 2050, and 2100, respectively (Rogelj et al., 2022). The corresponding deployment for limiting warming to 2°C requires 80, 2750 and 8960 $MtCO_2$/yr. for these years, respectively (Rogelj et al., 2022). Achieving CDR on this scale through Bio-CCS could, however, be limited by factors such as the cost of capturing CO_2, future biomass availability, social acceptance, lack of reliable long-term policy and the uncertainty of what a future negative emissions market will look like (Rodriguez et al., 2020). It is worth noting as well that dependence on Bio-CCS for CDR will only grow with further delay in deep emissions reduction, such that what is needed will likely go beyond technical and sustainable limits, emphasizing that Bio-CCS should not be regarded as the only solution to meet the climate targets.

The future potential for carbon capture in pulp and paper mills could also be affected by near-term implementation of methods for better usage of the biogenic carbon content of the feedstock. For example, lignin extraction where lignin can be used as feedstock for producing products with a long lifetime (Kuparinen et al., 2019) could be one such option. Although this does not have the same potential as carbon capture, the products made using lignin can displace fossil-based products[1], providing indirect reductions of fossil CO_2 emissions. One difference between utilizing carbon in products via lignin extraction versus Bio-CCS is that Bio-CCS can ensure permanent long-term storage and thereby contribute to carbon dioxide removal (CDR) from the atmosphere (negative emissions), while lignin-based products can contribute to emissions reductions through substitution effects.

In previous work in the ACCSESS project (reported in deliverable D5.2 (Svensson et al., 2023)), the heat integration potential for advanced CO_2 capture was investigated for a recycled paper mill located in Langerbrugge (Belgium) and a kraft pulp mill located in Skutskär (Sweden). The capture integration scenarios considered two different post-combustion capture (PCC) technologies: an amine-based (AMP/PZ) and an enzymatic carbonate-based (CO2 Solutions). The CO_2 Solutions™ technology from Saipem uses a non-toxic solvent and has a very low environmental impact. Furthermore, thanks to its lower regeneration temperature, this technology can utilize low-temperature excess process heat to meet part of the reboiler heat demand. This is an attractive feature for the pulp and paper industry where it is common to find significant amounts of residual heat at temperatures below 100°C (Svensson et al., 2019). Low-temperature excess heat could be used as a heat source also for the amine-based capture process if a heat pump is used to raise the temperature. This opportunity was also investigated in D5.2.

There exist some studies that have investigated cost estimations for CO_2 capture for the pulp and paper industry. However, the number of such studies is relatively small in comparison to other industries such as the cement or iron and steel industry. Furthermore, there is a lack of alignment between the reported cost estimates. This is partly due to the differences between each industrial

[1] https://www.storaenso.com/en/products/lignin

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site studied, such as excess heat availability, the concentration of carbon dioxide and other contaminants in the flue gas, the targeted capture rate, and the size of the flue gas flow. Site differences aside, discrepancies can also emerge due to differences in methodological framework, cost metric definitions, input data quality, choice of economic parameters (plant lifetime or discount rate for example), assumptions in technology maturity (first-of-a-kind (FOAK) vs. N^{th}-of-a-kind (NOAK) cost estimates) and the system boundaries i.e. whether transportation and long-term storage is included or not (IEAGHG, 2021).

This report presents the results of simulation of different post combustion capture scenarios for selected pulp and paper mills, and associated technoeconomic performance indicators. In particular, the report presents estimations of the CO_2 capture cost for advanced CO_2 capture integration configurations in one kraft pulp mill and one recycled paper mill. A qualitative discussion about how the CO_2 capture cost relates to the avoidance cost is also included.

1.1 Document Purpose

This deliverable presents results from Work Package 5 (WP5), Task 5.3, of the ACCSESS project. The report aims to evaluate the techno-economic feasibility of different heat integration scenarios for advanced CO_2 capture in pulp and paper mills.

1.2 List of Acronyms and abbreviations

AMP/PZ	AMP (2-amino-2-methyl-propanol) -PZ (piperazine)
APEA	Aspen Process Economizer Analyzer
BFB	Bubbling fluidized bed
Bio-CCS	Biogenic carbon capture and storage
BLG	Black liquor gasification
BP	Back-pressure
CAPEX	Capital expenditures
CCS	Carbon capture and storage
CCUS	Carbon capture utilization and storage
CDR	Carbon dioxide removal
CHP	Combined heat and power
COP	Coefficient of performance
DH	District heating
EPC	Equipment, procurement, and construction
FOAK	First-of-a-kind
GCC	Grand composite curve
HDC	Heat demand constrained (Scenario C)
LP	Low-pressure
MEA	Mono ethanol amine

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MVR	Mechanical vapour recompression
NOAK	N^{th}-of-a-kind
O&M	Operational & maintenance cost
OPEX	Operational expenditures
PCC	Post combustion capture
RDF	Refuse-derived fuel
SRD	Specific reboiler duty
TC	Turbine constrained (Scenario B)
TCR	Total capital requirements
TDC	Total direct cost
TEA	Techno-economic assessment
TPC	Total plant cost
TRL	Technology readiness level

1.3 Relation to other deliverables

This deliverable builds on the results from previous work in WP5, which have been reported in deliverable D5.2. D5.2 presents the selected pulp and paper mills that have been used to investigate the integration of advanced CO_2 capture configurations. D5.2 also describes the capture technologies and the process modelling and defines the different capture integration scenarios that are further evaluated from a techno-economic perspective in this deliverable.

The results from this deliverable, D5.3, will be used as input for further work in WP5 (opportunities for CDR from European pulp and paper plants, to be reported in D5.4) as well as in WP10 (e.g. D10.6, Prospective CCUS chains in Europe by 2025-2030)

1.4 Limitations

This document presents techno-economic results for two post-combustion capture technologies - AMP/PZ and CO2 Solutions. SINTEF modelled and simulated the AMP/PZ process to estimate utility requirements and equipment and installation costs, while Saipem designed and simulated the CO2 Solutions process for the corresponding estimations. Starting from the estimated equipment and installation costs, the same bottom-up approach for techno-economic assessment was used for both technologies to estimate the total capital requirements and capture costs (as detailed in (Becattini et al., 2024). However, different approaches were followed for the process inventory, equipment design, and estimation of equipment costs.

Here, SINTEF based their cost estimations on model results from Aspen Process Economic Analyzer, for which they followed standard assumptions for cost estimations used in the research community. Saipem, on the other hand, adopted the standard industrial practice, basing their estimations on vendor quotes and in-house evaluations. Since the two approaches differ, the resulting cost estimations for each capture technology may differ simply due to methodological differences, with the model-based approach often resulting in lower cost estimations.

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It is essential to emphasise the value of each approach and why they were used in the project. As mentioned above, the approach used by SINTEF has been widely used in the research community and by organisations such as the IEA Technology Collaboration Programme IEAGHG (IEAGHG, 2021). Adopting such an approach for the techno-economic analysis ensures alignment between the cost estimations presented in this work and other studies available in open literature, thereby facilitating comparisons and highlighting the potential for technology developments carried out in the ACCSESS project. From the perspective of Saipem, on the other hand, it is critical to ensure that cost estimations are performed using a procedure that reflects industrial state-of-the-art practices and the significant uncertainties which exist in the cost estimations.

The ACCSESS project realises the value of both these approaches. Thus, rather than trying to reconcile the approaches and produce results that do not satisfy any of the two opposing specifications mentioned above, the two independent approaches for process inventory, design and cost estimations have been used in the project. As discussed later in this report, the differences in modelling assumptions do not only affect the capital cost of the capture plants but also the operational cost. One of the main implications of this decision is that the results of the techno-economic analysis of the two capture solutions, AMP/PZ and CO2 Solutions, cannot be compared. The significant variation in methodology makes such a comparison pointless and invalid. Moreover, it is important to note here that carbon capture has not yet been implemented in the pulp and paper industry. Consequently, the cost estimations presented in this work, which represent potential costs for mature technology implementations (an nth-of-a-kind plant), are associated with significant uncertainties regardless of which approach is followed.

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2 BRIEF OVERVIEW OF STUDIED MILLS

The following section provides a summary of the production processes and the heat and power co-generation potential of the Paper Mill (Langerbrugge) and the Pulp Mill (Skutskär), highlighting what is of importance in relation to the capture plant and the heat integration scenarios, which will be discussed in the subsequent sections. A complete description of the two reference mills, including the full composition of the flue gases considered for capture and any other relevant data (steam header properties), can be found in Section 2 of D5.2 (Svensson et al., 2023).

As show in Figure 2.1, the electricity and steam demand for the production processes of the Paper Mill (de-inking & paper making) is met by two CHP plants, which operate using a variety of different fuels (biosludge, sewage sludge, waste wood and refuse-derived fuel (RDF)). Only approximately 70% of the electricity demand is met through on-site generation, with the balance imported from the grid. The point sources considered for capture are the two CHP plant boilers. The Paper Mill's annual CO_2 emissions are 0.61 Mt, where 73 % are considered biogenic with an overall CO_2 concentration of approximately 13 % (vol% dry). A 90% capture rate has been assumed for both the Pulp Mill and Paper Mill.

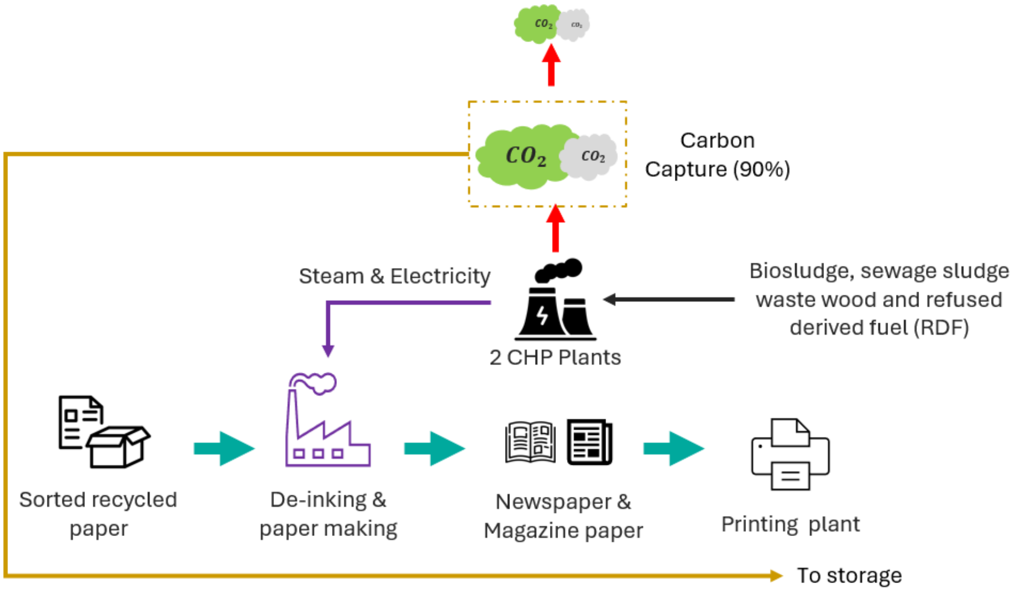

Figure 2.1:Overview of the Paper Mill's production process and heat and power co-generation potential (Icons from www.flaticon.com)

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For the Pulp Mill, the heat demand for the kraft pulping process is met primarily by the production of steam using high-temperature excess heat from two recovery boilers, see Figure 2.2. When the steam demand is greater than what can be supplied by the recovery boilers, steam is produced by a power boiler, which is operated using wood residues obtained from the debarking of the feedstock and purchased bark (if needed). Aside from supplying heat to the mill, the steam produced by the existing steam cycle is fed through a back-pressure turbine, which meets approximately 76% of the mill's annual electricity demand. The point sources considered for capture are the mill's two recovery boilers and the two lime kilns of the kraft pulping process. Emissions from the power boiler have not been considered for capture due to its large operational variations. Moreover, as will be seen in the subsequent sections, when looking to integrate the capture process, the load of the power boiler will vary depending on the heat integration scenario, and therefore so will its CO_2 emissions. The Pulp Mill's annual CO_2 emissions are 1.1 Mt, where all emissions are considered biogenic with an overall CO_2 concentration of approximately 16% (vol % dry).

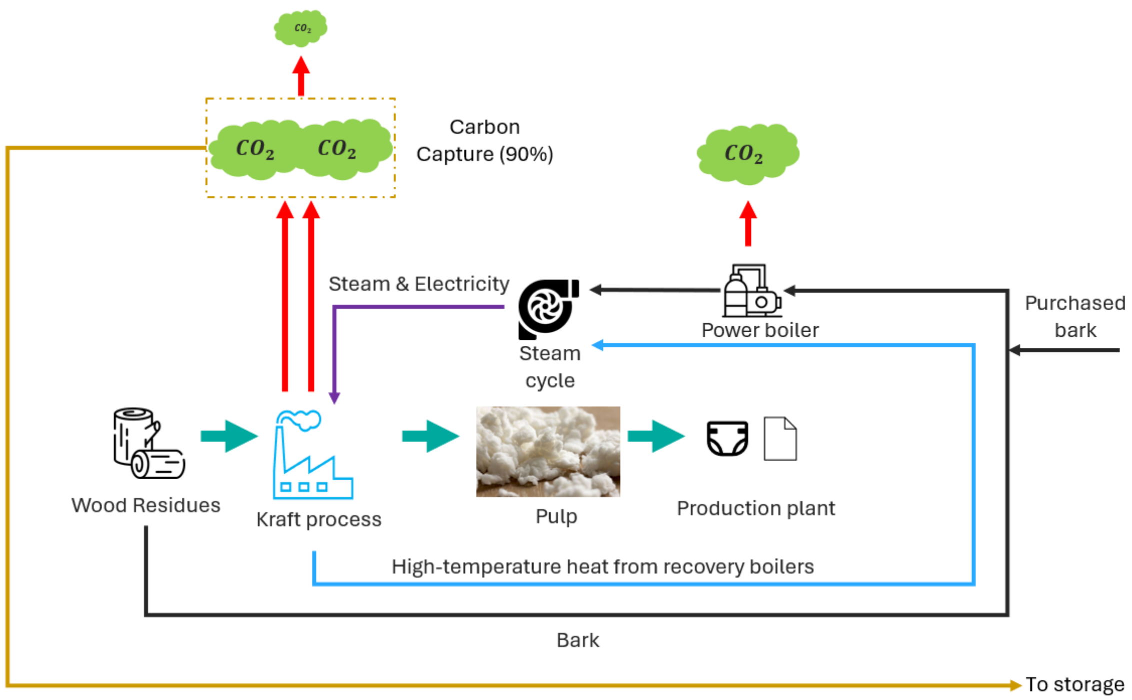

Figure 2.2: Overview of the Pulp's Mill's production process and heat and power co-generation potential (Icons obtained from www.flaticon.com)

To consider potential strategic developments in the Pulp Mill, a second scenario for carbon capture integration was defined for this mill. In this scenario, a process for lignin extraction is assumed to be implemented in the mill as a way to improve resource efficiency and extract more valuable bio-based products from the wood raw material. The extraction of lignin affects the energy balances of the mill as well as the amount of biogenic carbon dioxide available for capture.

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3 METHODOLOGY FOR THE TECHNO-ECONOMIC ASSESSMENT

The workflow for the techno-economic assessment (TEA) is depicted in Figure 3.1. As indicated in the grey box, mill data and process models developed in Task 5.1 and 5.2 (reported in previous deliverable D5.2 (Svensson et al., 2023)) have been used as input for this work. Any relevant economic parameters (cost of utilities and NOAK cost factors) are taken to follow the common ACCSESS framework assumptions.

The specific energy requirements of the capture and conditioning plant, including cooling, heating (specific reboiler duty (SRD)) and electricity, were estimated together with the associated equipment costs based on simulations using the process models completed in previous work. It is important to note that the modelling and simulations of the two capture technologies were performed following partly different methodologies and assumptions, potentially affecting not only the energy requirements (and thereby the operational expenditures (OPEX)) but also the equipment cost (capital expenditures (CAPEX)). In particular, the concentration assumed for the amine-based solvent has not been industrially proven, making the modelling assumptions for that technology highly theoretical. The carbonate-based technology, on the other hand, has been tested in commercial-scale demonstration plant and is in the industrialization phase for some applications. Consequently, for this technology, the design and cost estimations could be derived from industrial experience rather than only from theoretical studies. Moreover, only one design configuration was explored for each of the technologies, and neither were optimized for improved performance or lower CAPEX. As a result, despite having followed the same overall workflow for performing the TEA, the resulting estimated performance of the two technologies should not be directly compared. Section 3.1 describes the process modelling in more detail.

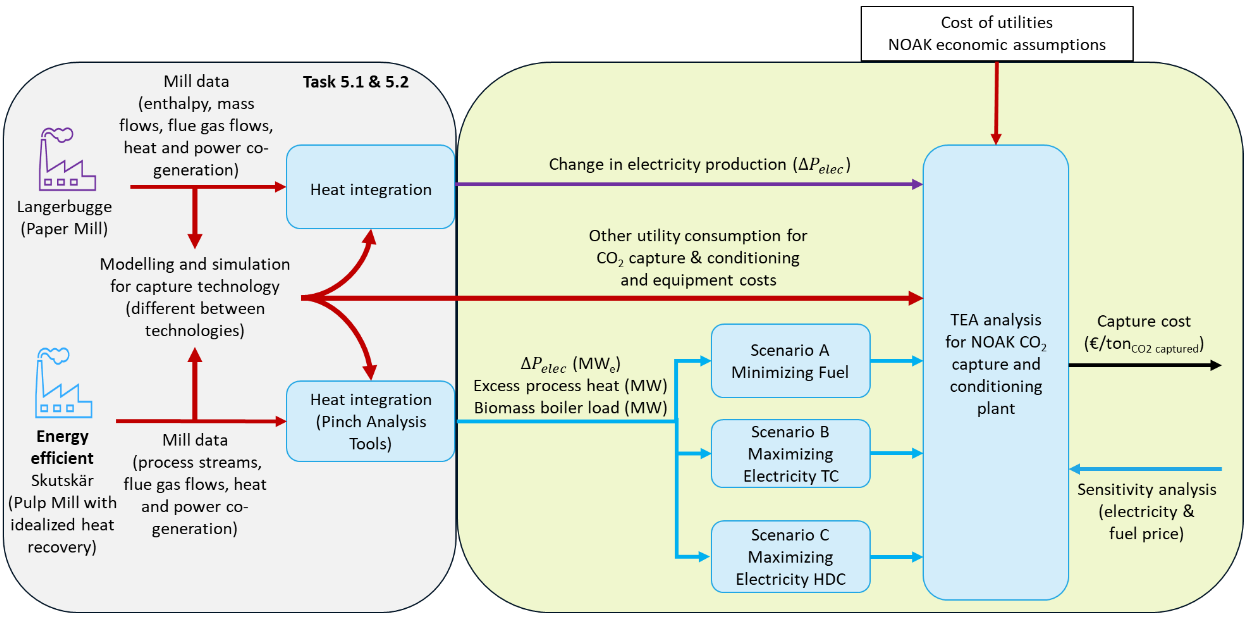

Figure 3.1: Workflow for techno-economic assessment

In addition, the methodology followed for heat integration differs between the two mills. Unlike the Skutskär pulp mill, the production process of the Langerbrugge Paper Mill is relatively simple with limited potential for heat recovery. Consequently, steam balance calculations can be used to estimate the effect of integrating the capture process. For the pulp mill on the other hand, there is

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a large potential for internal process heat recovery within the mill, most of which is already exploited in an extensive heat recovery system. Potential effects on fuel demand and power co-generation in the Pulp mill were therefore evaluated using a different method based on pinch analysis. Section 3.2 further explains the methodology followed for integration of the capture process in the mill.

3.1 Process Modelling of the Carbon Capture Technologies

The AMP/PZ process was modelled and simulated using Aspen Plus v10 for the two mills, whereas the CO2 Solutions™ process was simulated using Protreat 6.6 (Optimized Gas Treating Inc. 2001). The simulation results, specifically the energy requirements for capturing and conditioning of each technology, were used as input data for the heat integration analysis. Furthermore, the simulation results were also used as a basis for estimating equipment and installation costs for the capture and conditioning plant. For the AMP/PZ process and the conditioning plant, costs were estimated using the Aspen Process Economic Analyzer, while for the CO_2 Solutions process, these costs were obtained from assumptions based on a database of past enquiries to suppliers of similar equipment.

The carbon capture process for the Pulp mill with lignin extraction was not simulated explicitly. Instead, based on the assumption that the CO_2 concentration of the flue gases would remain the same, the specific energy requirements were assumed to be the same as for the mill without lignin extraction. Capital costs were also based on the estimations made for the mill without lignin extraction but scaled using an exponent to adjust for the lower CO_2 flow.

For the AMP/PZ process, the solvent composition was chosen to be 33 wt% AMP – 12 wt% PZ. It is worth noting that this composition differs from that reported in literature, where 40% is indicated as the best concentration by most studies. The higher amine concentration (of 45%) assumed in this work benefits the capture efficiency and lowers the specific reboiler duty, but it has not been industrially tested and could potentially lead to problems with, for example, corrosion or foaming. Given that this concentration has never been industrially proven, it is also important to note that the simulations results for AMP/PZ technology have not been validated against industrial operating data.

The carbonate-based technology has been tested in commercial-scale demonstration plants and is in the industrialization phase for some applications. Consequently, for this technology, the design and cost estimations could be derived from industrial experience rather than only from theoretical studies. Only one design configuration was explored for each of the technologies, and neither were optimized for improved performance or lower CAPEX.

3.2 Integrating Carbon Capture with Reference Mills

To evaluate the cost of implementing carbon capture, a thermodynamic analysis was first performed to determine the heat and power co-generation potential of the integrated system. In all cases (the Pulp or Paper Mill), the energy balance of the mill is directly affected by the need for low-pressure (LP) steam to cover all or part (in the case of the CO2 Solutions process) of the heat demand of the stripper reboiler. This will typically result in a loss in power production (or possibly in an increased demand for fuel), in addition to increasing the mill cooling water and electricity demand. All of which influence the operational cost of carbon capture. The magnitude of the impact on the mill's energy balance depends on the technology and on the way in which the integration is implemented.

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3.2.1 Paper Mill

Due to limited opportunity for improved heat recovery, the heat demand for both capture processes can only be met by LP steam (2.2 bar(g)), produced by the two co-generation plants of the Paper Mill. Namely, from the steam flow passed through the condensing stage turbine of one of the co-generation plants. The thermodynamic analysis consequently consisted of calculating the mass flow of the LP steam required to meet reboiler duty of the capture process, and then evaluating how this steam extraction influences the net power output of the mill. Available operational data for the mill as it exists today (see D5.2 (Svensson et al., 2023)) is considered representative for quantifying the energy penalty of implementing carbon capture. It should be noted that using the same heat source to meet the heating demand for capture, regardless of the capture process, ignores the advantage that the CO2 Solutions process has over the AMP/PZ process, which is the possibility to use heat at a lower temperature.

3.2.2 Pulp Mill

As described in more detail in D5.2 (Svensson et al., 2023), a two-step process based on pinch analysis was followed where first the maximum heat integration potential between the mill and the capture process was determined, followed by estimating the effect that this integrated pulping and capture process has on the power co-generation potential of the mill. This was done following the method proposed by (Svensson et al., 2019) for estimating the potential availability and the trade-offs for recovery of excess. The trade-offs investigated in D5.2 were minimizing fuel use or maximizing electricity production. However, in this work, a third integration scenario was added, in which limitations on power generation capacity at the mill site have also been considered when optimizing for electricity production.

It is important to note that adopting a pinch analysis approach, the maximum internal heat recovery within the mill, and between the mill and the capture process, is estimated without taking into consideration limitations on process layout. The downside of this approach is that it is unlikely that the ideal heat integration scenarios identified in this work can be fully realized in an actual process. Be that as it may, providing a detailed design of an optimized heat recovery system for a specific mill is not the aim of this work. This work aims to explore and compare the economic performance of different possible heat integration scenarios for a pulp mill. For these comparisons to be fair, they must all have the same reference point i.e. it would be unfair to compare the performance of an optimized integrated mill (one obtained from energy targeting using pinch analysis) to a non-optimized configuration (present day pulp mill). This means that by using pinch analysis tools, the base case mill for this analysis is a more energy-efficient compared to the existing pulp mill. This is consistent with the previous assumption that the implementation of carbon capture will occur in the future, where it is likely that the mill has implemented measures to improve its energy efficiency.

The effect that the integrated pulping and capture process has on power co-generation potential of the on-site steam cycle was then evaluated by optimizing the size of the steam cycle based on selected trade-offs between minimizing fuel use and maximizing electricity production. A simplified steam cycle was assumed for heat integration where it was assumed that the turbines could be by-passed to deliver LP steam (3 bar(g)) to the process without co-generation of power. In the case of minimizing fuel use, the heat cascades of the steam cycle were optimized with the aim of minimizing hot utility use (i.e. fuel use in the power boiler). This optimization scenario will henceforth be referred to as Scenario A (referred to as 'Minimized fuel use' in D5.2). As for maximizing electricity generation, the additional LP steam demand incurred by the

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implementation of the capture plant allows the potential to generate more back-pressure power than in the reference mill without carbon capture. However, this would require investing in an additional turbine, as the Pulp Mill's existing turbine capacity is not sufficient to fully harness this additional back-pressure power generation potential. Two possible heat integration scenarios have therefore been explored when optimizing for maximum power generation: one that is constrained by existing turbine capacity (Scenario B) (not included in D5.2) and one that is constrained by the minimum heating demand of the mill, which has now increased due to the implementation of carbon capture (Scenario C) (referred to as 'Maximized power generation' in D5.2). The limit imposed on power generation was 46 MWe, as this is the size of the turbine of the existing pulp mill that is being modelled.

All the energy targeting computations, including the integration of carbon capture with the mill, were updated for the work conducted within D5.3 based on new input data from capture simulations and adjustments in assumptions and data for the mill processes and steam cycles. This has led to some changes in results compared to what was presented in D5.2 (see Appendix A for a summary of the main differences). The impact that each scenario has on fuel input and electricity production, relative to the base case pulp mill without carbon capture, can be observed in Table 3.1.

Table 3.1: Changes in heat input and electricity production for all heat integration scenarios relative to the base case for Pulp Mill without lignin extraction

Parameter	Scenario A1 Minimizing Fuel Use	Scenario B1 Maximizing Electricity Production – turbine constrained (TC)	Scenario C1 Maximizing Electricity Production – heat demand constrained (HDC)
Fuel Input	Unchanged	▲	▲
Electricity Production (46 MWe)	▼	Unchanged	▲

The heat and power co-generation potential of a Pulp Mill with lignin extraction was evaluated following the same process as described above, where the base case for such a mill is a futuristic and efficient mill *with* lignin extraction. The reader is encouraged to consult D5.2 (Svensson et al., 2023), and other relevant literature such as (Vakkilainen et al., 2009; Välimäki et al., 2010), for a more detailed explanation on how lignin extraction affects the standard operation of a recovery boiler in a pulp mill, as well as how it affects the energy balance and CO_2 emissions of the pulp mill.

Most importantly in relation to the capture plant, extracting lignin from the strong back liquor reduces the available high temperature excess heat of the recovery boilers by reducing the carbon that can be combusted. Therefore, it may be possible that additional fuel will be required to ensure that there is sufficient heat to meet the process heating requirements of the mill and the heating demand for carbon capture, regardless of the selected capture technology. In addition, because of the reduction in excess heat, the power production of the Pulp Mill with lignin extraction without capture is reduced from 46 MWe to 40 MWe. The changes in heat input and electricity production of each heat integration scenario relative to the base case with lignin extraction are shown below in Table 3.2.

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Table 3.2: Changes in heat input and electricity production for all heat integration scenarios relative to the base case for the Pulp Mill with lignin extraction

	Scenario A2 Minimizing Fuel Use	**Scenario B2 Maximizing Electricity Production – turbine constrained (TC)**	**Scenario C2 Maximizing electricity production – heat demand constrained (HDC)**
Fuel Input	Increased or unchanged	▲	▲
Electricity Production (40 MWe)	▼	▲	▲

The reader is encouraged to revisit these two tables when reading the subsequent sections of this report, as the aim here is to also define the nomenclature of each scenario clearly, where 1 and 2 differentiate between a pulp mill without lignin extraction and a pulp mill with lignin extraction, respectively. Instances where the scenarios are referred to without specifying 1 or 2, for example Scenario B, signifies that what is written applies to both pulp mills.

3.3 Economic Assessment: Capture Cost

With the focus of WP5 being on the integration of the capture process in the pulp and paper mills, the key economic indicator selected to evaluate the cost for different integration scenarios is the capture cost. The capture cost can be used as a basis for further evaluation of costs along the whole CCS value chain, as well as relative to achieved CO_2 avoidance. However, to be able to estimate avoidance costs for the whole CCS chain, information would also be required about the costs and emissions related to transport and storage of CO_2. Nevertheless, some estimations of avoidance costs are presented in Section 4.4, together with a further discussion.

The CO_2 capture cost was calculated based on estimations of OPEX and CAPEX for the capture and conditioning plant assuming fixed annual costs (annuity method). As defined in Equation 1, this relates the cost needed to build and operate the capture and conditioning plant to the total amount of CO_2 captured and conditioned by the plant. This definition for the capture cost follows what has been recommended for improved carbon capture evaluations (Roussanaly et al., 2021).

$$Capture\ cost = \frac{C_{CAPEX} + C_{OPEX,fix} + (C_{electricity} + C_{OPEX,other} + C_{fuel})}{CO_2\ captured}$$

where CO_2 captured is based on a 90% capture rate, C_{CAPEX} is the annualized capital investment for the capture and conditioning plant and $C_{OPEX,fix}$ is the fixed annual operational costs for capture and conditioning. The variable OPEX has been split into three terms where $C_{electricity}$ includes the electricity demand of the capture and conditioning plant, as well as the net change in electric power production due to the additional heat demand for capture. $C_{OPEX,other}$ includes cost of material consumptions (process, solvent, and cooling water), whereas C_{fuel} is the cost of additional fuel for steam production. Lastly, $C_{OPEX,fix}$ includes maintenance, insurance, and labour cost. The parameters assumed for the operational costs are shown in Table 3.3. Note that the cost of the first fill of solvent was not included in the total cost for any of the technologies.

The capital investment for the capture and conditioning plant of both technologies was evaluated using a bottom-up cost estimation approach, where the total capital requirements (TCR) were estimated by applying cost factors to estimated equipment and installation costs (EC+IC) for

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individual equipment. The cost factors were chosen according to an n[th]-of-kind (NOAK) approach, since it is assumed that the retrofit will occur in the future, where carbon capture integration with the pulp and paper industry has reached a greater level of maturity. Note, however, that it is not possible to state how much capacity expansion would be needed for the capture technology until NOAK cost levels are reached, since this would depend on the first-of-a-kind (FOAK) cost levels as well as the potential learnings between projects (learning rate) (Beiron & Johnsson, 2024). The contingencies and other cost factors considered in the bottom-up estimation of the total capital requirements (TCR) cost for capture and conditioning are detailed in Table 3.3.

When evaluating the capture cost for a Pulp Mill with lignin extraction, the TCR of the capture and conditioning plant was multiplied by a scaling factor to account for the reduction in equipment size due to the reduction in CO_2 captured. The scaling factor to scale the CAPEX of the reference plant for a plant with different flue gas size but with the same CO_2 flue gas concentration was obtained using the equation below:

$$C_i = C_{ref}\left(\frac{CO2_{emissions,i}}{CO2_{emissions,ref}}\right)^n$$

where the scaling exponent, n, was obtained from (Garðarsdóttir et al., 2018) and is dependent on the CO_2 flue gas concentration (0.61 for 16 vol% dry). It should, however, be noted that other studies suggest scaling exponents as high as 0.75-0.9 (Roussanaly et al., 2017), which implies that the applied value is rather optimistic.

Table 3.3: Main parameters and assumptions for economic assessment

Key economic parameters specific to each mill		
	Paper Mill (Belgium)	Pulp Mill (Sweden)
Electricity price, €/kWh	0.076[a]	0.045[b]
Operating hours, hours/year	8000	8400
Annual Labour cost, k€/year	60[c]	86[c]
Parameter	**Value**	**Unit**
Main process assumptions and parameters		
Capture Rate	90	%
Scaling factor for TCR of capture plant in mill with lignin extraction	0.93	-
CAPEX[d]		
Plant lifetime	25	years
Discount rate	8	%
Construction time	2	years
From Equipment Cost (EC) and Installation Costs (IC) to TCR		
Total direct cost without process contingencies (TDC')[e]	EC+IC[e]	€
Total direct cost incl process contingencies (TDC)	TDC'*1.10	€
Engineering, procurement, construction (EPC)	TDC*1.15	€
Total Plant Cost (TPC)	EPC*1.30	€
Total Capital Requirements (TCR)[f]	TPC*1.275	€
Overnight factor	1.18	-

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Table 3.3 continued

Variable OPEX[g]		
AMP	8	€/kg
PZ	6	€/kg
Enzyme	441.6	€/kg
Carbonate	0.46	€/kg
Cooling water[h]	0.039	€/m^3
Process water[h]	6.65	€/m^3
Wood Chips (for additional hot utility demand)	18	€/MWh
Fixed OPEX[h]		
Maintenance	2	%TPC
Labour	0.8	%TPC
Insurance and local property	2	%TPC
Administrative & support labour	30	%(O&M)
Operating Labour - Employees for capture	10	employees
Operating labour - Employees for conditioning	5	employees

[a] Median EU27 – Band IF 2020[2]
[b] Sweden – Band IF 2020[4]
[c] Labour cost levels for industry except construction: based on the Labour Cost Survey performed by Eurostat from[3] and includes compensation of employees plus taxes minus subsidies
[d] All NOAK cost factors assumed in this work (lifetime, discount rate and contingencies such as process, system, project and indirect cost) were taken from Table C.7 in (Becattini et al., 2024)
[e] Equipment cost (EC) and installation cost (IC)
[f] Includes owner's cost, start-up modification, start-up spare parts and the overnight factor
[g] Obtained from literature (AMP/PZ (Manzolini et al., 2014), enzyme & carbonate (Gilassi et al., 2020) and wood chips[4])
[h] Also obtained from (Becattini et al., 2024)

The cost of any additional equipment required for the integration of carbon capture with both mills was estimated using relevant cost functions, as shown in Table 3.4. Note that all the costs were computed in €$_{2020}$. The cost of any additional heat exchangers required was estimated using Aspen Process Economizer Analyzer (APEA). In the case of the Pulp Mill, there are additional equipment costs to be considered, depending on the heat integration scenario. For Scenarios B and C, the additional hot utility demand was assumed to be covered by a biomass boiler using wood chips as a fuel. For Scenario C, the cost of investing in additional turbine capacity is included in the TCR, in addition to investing in a biomass boiler.

[2] Eurostat https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204/default/table?lang=en Accessed 22.08.2024
[3] Eurostat https://ec.europa.eu/eurostat/web/labour-market/database Accessed 22.08.2024
[4] Wood fuel and peat prices https://pxexternal.energimyndigheten.se/

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Table 3.4: Equipment cost estimations (M$) for additional equipment required for integration

Equipment	Units for size calculation (S)	Cost function	Reference
Heat exchanger	Area of the HX (m^2)	Aspen Process Economizer Analyzer (APEA)	-
Biomass boiler (CFB)[a]	Heat output (MW_{th})	$C = 471\left(\frac{\dot{Q}_{MW_{th}}}{1521}\right)^{0.67}$	(Castilla et al., 2021)
Turbine[b]	Power (kW)	$C = 15\,215 + 656S^{0.8}$	(Towler et al., 2008)

[a] Original equipment cost in $\$_{2021}$
[b] Original equipment cost in $\$_{2006}$

The equipment cost shown for the biomass boiler was originally developed by (Castilla et al., 2021), who used it to estimate the cost for a carbonator by approximating it as a circulating fluidized bed (CFB). Castilla et al. found a lack of consistency between other equipment cost functions reported, notably the scaling factor (shown as 0.67 in Table 3.4 above) varied significantly. Therefore, the cost function developed in their work was based on other reported cost functions but corrected using cost data from a realized project (Thunman et al., 2019). Whether this cost function yields a better approximation for the biomass boiler is uncertain, adding to the uncertainty that already exists with the capital cost estimates for the capture and conditioning plant.

3.4 Integration of a Heat Pump with the AMP/PZ Capture Process

In previous tasks in WP5, the potential for using a heat pump to supply parts of the heat required for solvent regeneration was investigated for the AMP/PZ process, see D5.2 (Svensson et al., 2023). The analysis showed that heat pumping could be a very promising opportunity in the Pulp Mill, if it is possible to realize the large theoretical potential for excess heat identified from the pulp mill processes. According to the excess heat targets, it was found that almost 28 MW of process heat could be released in the form of flash steam at temperatures slightly above 100 °C. This flash steam also constitutes a major part of the process excess heat that was considered as a heat source for the CO2 Solutions process. With the use of a heat pump, the flash steam could instead be used as a heat source for the AMP/PZ process, removing some of the need for LP utility steam.

By using a mechanical vapour recompression (MVR) heat pump, the flash steam can be used directly after compression. Consequently, this avoids the need for heat exchange with an intermediate working media. It is important to note that should the MVR be implemented; the quality of the flash steam should be verified to ensure it is suitable for a compressor i.e. there is no risk of corrosion on the compressor blades from any impurities. With the regeneration temperature for the AMP/PZ solvent at 116 °C, this limits the required temperature lift for the heat pump to 24 °C only, thus allowing for a high coefficient of performance (COP). Table 3.5 summarizes estimated design and performance data for the heat pump.

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Table 3.5: Key design and performance data for the heat pump

Parameter	Value
Excess heat in flash steam	27.6 MW at 102°C
Temperature lift	24 °C
COP	11.6 (assuming a Carnot COP factor of 70%)
Delivered heat	30.2 MW at 126 °C saturation temperature
Electric power demand	2.6 MW

The specific cost for a heat pump of this size was estimated using a cost correlation from (Klute et al., 2024):

$$Cost_{\mathrm{MVR}} = 385.16\ Q^{-0.339}\ [\mathrm{EUR/kW_{th}}],$$

where Q is the heat delivered by the heat pump. This cost is assumed to represent the total direct cost for the heat pump installation, i.e. including equipment and installation costs. To estimate the total capital requirement, the same cost factors were used as for the capture cost estimations in this work (see Table 3), but for simplicity start-up costs were neglected. In addition to the cost for the heat pump itself, it is also necessary to replace the single reboiler for the solvent regeneration stripper with two smaller reboilers – one using low-pressure utility steam as a heat source, and one using the recompressed flash steam. Considering the small temperature difference between low-pressure utility steam and recompressed flash steam this is not assumed to have a significant influence on the total required heat transfer area. However, the cost of having two reboiler units is expected to be higher than only having one. As a conservative estimate, the reboiler cost is assumed to double when integrating the heat pump.

The integration of the heat pump also affects other cost components considered in the techno-economic estimates of the CO_2 capture cost:

- Electricity (2.6 MW) is needed to drive the heat pump
- Process cooling (27.6 MW) is avoided by instead recovering the excess heat.
- Utility (LP) steam demand for the reboiler duty is reduced by ca 30 MW. This has implications for electricity and/or fuel balances in the mill depending on the heat integration scenario considered.
    - Scenario A1 – Minimizing Fuel Use: By using recompressed flash steam instead of by-passing the turbines, the loss in electricity generation can be reduced.
    - Scenario B1 – Maximizing Electricity Production – turbine constrained: The heat pump makes it possible to reduce the additional fuel input and boiler capacity investment that would otherwise be required to maximize the utilization of the existing turbine capacity.
    - Scenario C1 – Maximizing Electricity Production – heat demand constrained: The heat pump reduces the potential for back-pressure power generation (and corresponding biomass boiler load) by decreasing the demand for low-pressure utility steam. At a certain amount of heat delivered from the heat pump, the potential for power co-generation will be reduced to be within the capacity of the existing turbine, thereby making Scenario C1 identical to Scenario B1.

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3.5 Sensitivity Analysis on Price of Fuel and Electricity

As the future price of electricity and fuel (wood chips) is uncertain, a sensitivity analysis was conducted to evaluate the impact of future energy markets on the capture cost of the heat integration scenarios. Moreover, whether a heat integration scenario performs better economically compared to another is likely to vary depending on the energy market. For all scenarios and both technologies, the capture cost was evaluated for electricity prices between 20 and 300 €/MWh, at three different wood chip prices (9, 18 & 27 €/MWh). The motivation behind exploring a large range of electricity price is to demonstrate what the capture cost could be for a pulp mill located somewhere other than Belgium or Sweden. Following this, the lower and upper value were selected based on what has been observed in Europe over the past 10 years[5]. It is worth noting that capture cost obtained from such an analysis would not be exactly representative of the capture cost for a mill in another location as other parameters which are dependent on location, such as labour cost, were kept constant.

3.6 Integrated System: CO_2 Emissions

The CO_2 emissions of the Pulp Mill equipped with carbon capture will vary depending on the technology and the way in which the integration is realized i.e. whether fuel use is minimized, or electricity generation is maximized. When minimizing fuel use, the decrease in electricity production combined with the electricity demand of the capture and conditioning plant, will result in the need to import electricity from the grid. Consequently, this will result in indirect (fossil) emissions. As for maximizing electricity generation, electricity production is maintained (Scenario B) or increased (Scenario C) by additional (biomass) fuel consumption, resulting in direct (biogenic) emissions. Depending on the technology, the additional electricity gain in Scenario C may be enough to meet the electricity demand for capture and conditioning, and as well provide electricity for the other operations of the mill. If that is the case, this will result in a decrease in indirect fossil emissions as it would replace electricity provided by other generators. The upstream emissions associated with the additional biomass use in Scenario B and C (land-use changes, harvesting and transportation) have been neglected.

In the case of the Paper Mill, the integration of carbon capture is like Scenario A for the Pulp Mill, where the loss in electricity generation, combined with the electricity demand of the capture and conditioning plant, result in indirect (fossil) emissions related to the import of electricity from the grid. The emissions intensity assumed for electricity in Belgium (Paper Mill) and Sweden (Pulp Mill), as well as the emissions intensity of the fuel for the biomass boiler in Scenario B and C, is detailed in Table 3.6.

Table 3.6: Assumed data for calculating CO_2 emissions from electricity and biomass boiler

	Value	Unit
Belgium: electricity emissions intensity	230.70[a]	$kgCO_2/MWh$
Sweden: electricity emissions intensity	8.80[a]	$kgCO_2/MWh$
Wood chips	95[b]	$kgCO_2/GJ$

[a] EU27 emissions intensity used for Belgium and Sweden[6]
[b]Assumed wood bark with constant carbon content of 53.1 Carbon wt% (dry and ash free basis) from Table 5 in (Demirbas & Demirbas, 2009)

[5] Eurostat https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table?lang=en Accessed 22.08.2024
[6] https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1 Accessed 20.04.2024

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4 RESULTS

4.1 Energy Required for the Integrated Mill and Capture System

4.1.1 Paper Mill

The steam network of the integrated system (Paper Mill with carbon capture) is shown below in Figure 4.1. For both the AMP/PZ and CO2 Solutions process, the condensing stage of the turbine T2 is bypassed so that all the steam flow is extracted to the 2.2 bar(g) header. In the case of the AMP/PZ process, a complete bypass would not be required to cover the reboiler duty of the capture plant. However, the steam flow remaining in the turbine would be too low to operate the turbine condensing stage and, consequently, a full by-pass is assumed anyway. For the CO2 Solutions process, the entire steam flow through the condensing stage would be needed to meet the reboiler duty, which means that a full bypass is required.

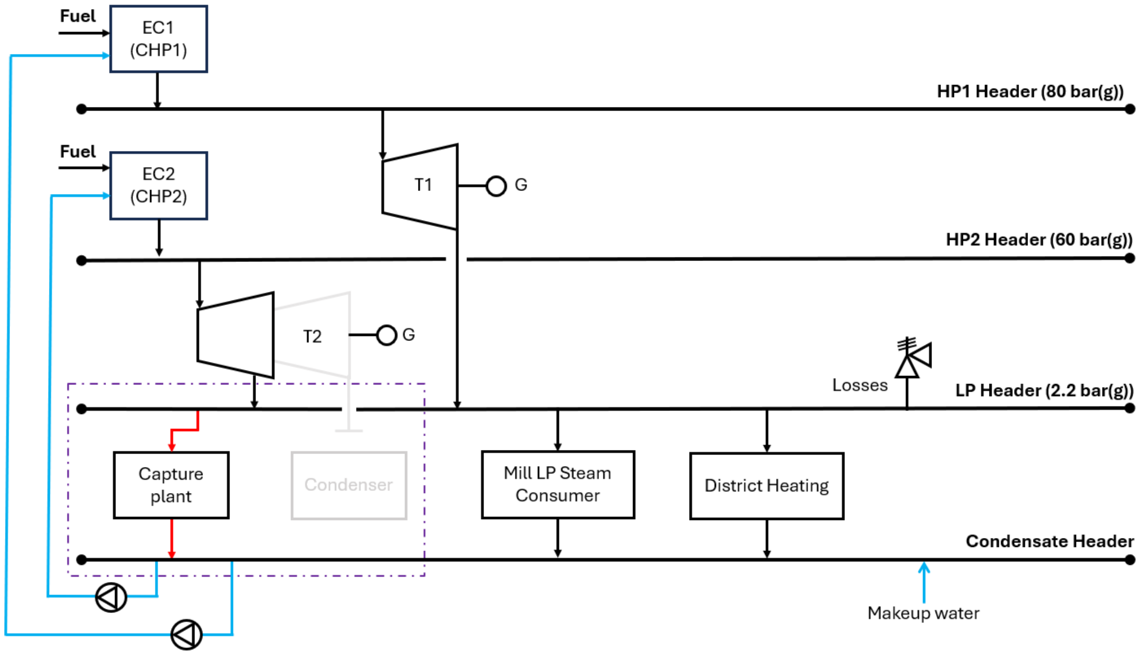

Figure 4.1: Steam network for the Paper Mill with carbon capture where the purple dashed box represents the main modifications to the system, which includes the bypass of condensing stage and the additional LP heat demand of the capture plant for both technologies. EC1 and EC2 are the boilers in CHP1 and CHP2, respectively. T1 is a back-pressure turbine whereas T2 is a condensing turbine. Note that key aspects of the steam network such as the accumulator tanks and pressure reducing valves for example, these have been omitted for simplicity.

Since the condensing stage is fully bypassed for both technologies, the loss in power generation is the same. Consequently, the specific cost for LP steam per tonne of CO_2 captured is the same despite their different SRDs. However, the two technologies differ with respect to the excess heat (LP steam) remaining after integration, although this is not reflected in the capture cost. As detailed in Table 4.1, the remaining excess heat is approximately 5 MW for the AMP/PZ process and 0 MW for the CO2 Solutions process. This would need to be cooled away as there is no use for this heat, thereby increasing the mill's cooling demand. Alternatively, this could be used for district heating in the future, providing an additional source of revenue to the Paper Mill. The integration of the AMP/PZ process with the Paper Mill could have been optimized to avoid having additional excess heat leftover, for example reducing the fuel input. However, this would affect the capture plant as there would less CO_2 available for capture, requiring iterative re-modelling of the capture plant and steam system. This was therefore not further explored.

Table 4.1: Power production and excess heat availability for the integrated system (carbon capture and Paper Mill)

	Power produced (MWe)	Loss in power generation (MWe)	Heat cooled in Turbine Condenser (MW)	Excess LP Steam (MW)
Reference Paper Mill (no capture)	47.2	-	54*	-
AMP/PZ process & Paper Mill	34.9	12.3	0	4.9
CO2 Solutions & Paper Mill	34.9	12.3	0	0

*Approximate heat flow rejected to cooling tower based on the average annual values

As the temperature of the heat supply to the CO2 Solutions process is higher than 90°C, the LP steam extraction is used to produce hot water from 75°C to 85°C. Two heat exchangers (HX) were explored, one where the steam is condensed without subcooling and another with approximately 28 K of subcooling. The motivation behind exploring two different heat exchanger designs is due to the variation in excess steam available between seasons, where more steam is available during summer when there is no demand for district heating. The HX with 28 K subcooling respects the maximum available excess steam flow of the condensing stage of T2 (see Figure 4.1) when the Paper Mill provides district heating.

Despite the need for subcooling, the temperature of the feedwater after the heat exchanger would be higher than what it would be if the condensing stage were not bypassed. Given that there is already an existing steam demand for feedwater heating, it can therefore be assumed that the Paper Mill will not incur any additional cost for condensate pre-heating. The specifications of the two heat exchangers are detailed in Table 4.2, where it can be observed that the difference in cost between the two appears to be significant but was found negligible in the final cost estimate.

Table 4.2: HX Specifications for heat exchange between mill and CO2 Solutions process

	HX Area (m2)	Cost (M€)
HX no subcooling	418.2	0.27
HX 28 K subcooling	564.9	0.36

4.1.2 Pulp mill

The way in which the steam network of the Pulp Mill is affected by the integration of carbon capture depends on both the heat integration scenario (see Table 3.1 and Table 3.2) and on the capture technology. It is therefore difficult to comprehensively depict the modifications required in the steam network. In the case of the AMP/PZ process, the reboiler duty is met completely by LP steam. As for the CO2 Solutions process, the heat integration results showed that approximately 38 MW excess heat (at approximately 100°C) could be used to meet the reboiler duty, with the remaining met by LP steam.

In Scenario A, the high-temperature excess heat from the recovery boilers is not enough to meet the added heat demand of the capture process and maintain power production. Because of this, part of the high-temperature excess heat is utilized without co-generation of power. As shown in Figure 4.2, this power loss is lower when integrating the Pulp Mill with the CO2 Solutions process since it has a lower LP steam demand, thanks to the possibility to use low-temperature process excess heat. Consequently, the CO2 Solutions process has a lower fuel demand compared to the AMP/PZ process in Scenario B1 (24 MW vs. 5 MW). Recall that in this scenario, the Pulp Mill

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invests in a biomass boiler to ensure that there is enough heat to restore full power production and to meet the heating demands of integrated system. Furthermore, due to its lower LP steam consumption, the minimum heating demand of the mill once integrated with the CO2 Solutions process is lower compared to the AMP/PZ process. This results in a smaller potential for additional electricity production in back-pressure steam turbines for the CO2 Solutions process in Scenario C (61 MW_e vs. 57 MW_e).

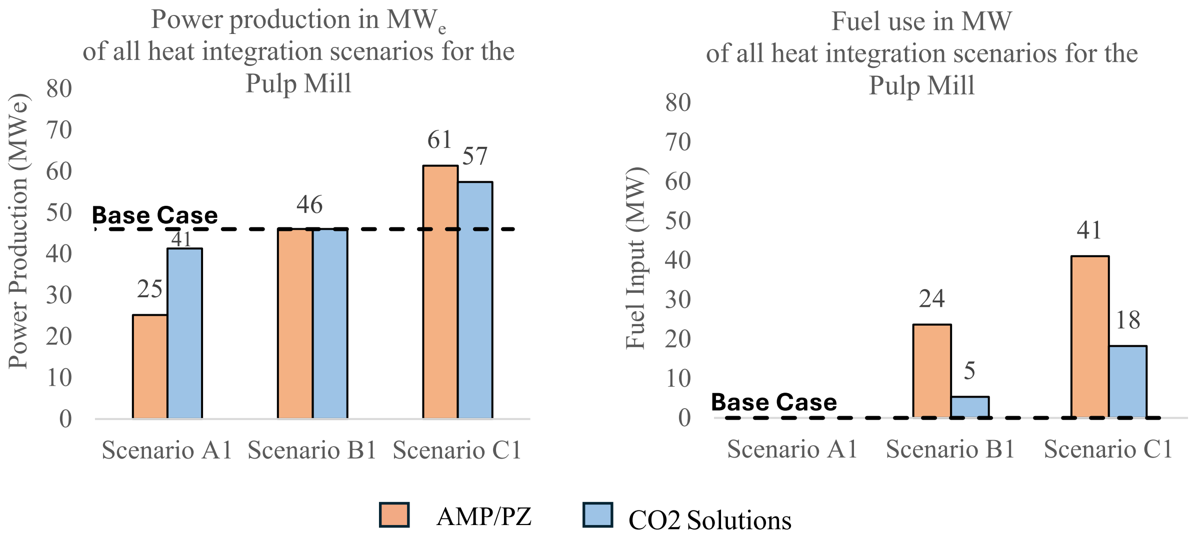

Figure 4.2: Power production (left) and fuel input (right) for the integrated system in all heat integration scenarios for the mill without lignin extraction. Scenario A1: Minimized fuel use, Scenario B1: Maximized power generation with existing turbine capacity, Scenario C1: Maximized back-pressure power generation as limited by back-pressure steam demand, but with no turbine capacity constraints. The electricity generation of the base case is 46 MWe where the fuel input is zero as there would be no need to increase fuel consumption without carbon capture.

When looking at the results for the Pulp Mill with lignin extraction in Figure 4.3, it can be observed that all the electricity production is lost for both capture technologies. What is not shown is that, in the case of the CO2 Solutions process, not all the excess heat from the recovery boilers is required to meet the heat demand for capture, i.e. full flue gas heat recovery is not required. However, if the heat remaining were to be used for steam generation, the steam flow through the turbine would be below the minimum flow requirement for operating the turbine. Nevertheless, the greater excess heat availability from the recovery boiler reduces the amount of additional fuel needed to restore power production for the CO2 Solutions process compared to the AMP/PZ process in Scenario B2 (55 MW vs. 36 MW).

One should also note that the power production in Scenario B2 is fully restored to what it could be in a mill without lignin extraction (46 MWe), resulting in a gain in electricity generation of 6 MWe. This increase in power generation could have been obtained even without the carbon capture integration, but would then require investment in a new boiler, with very small capacity and consequently high specific cost only to gain these few MW of electricity. In a way, the implementation of carbon capture on the mill with lignin extraction further justifies the investment in additional boiler capacity to restore full power generation as its more economically attractive to invest in a larger boiler (economies of scale).

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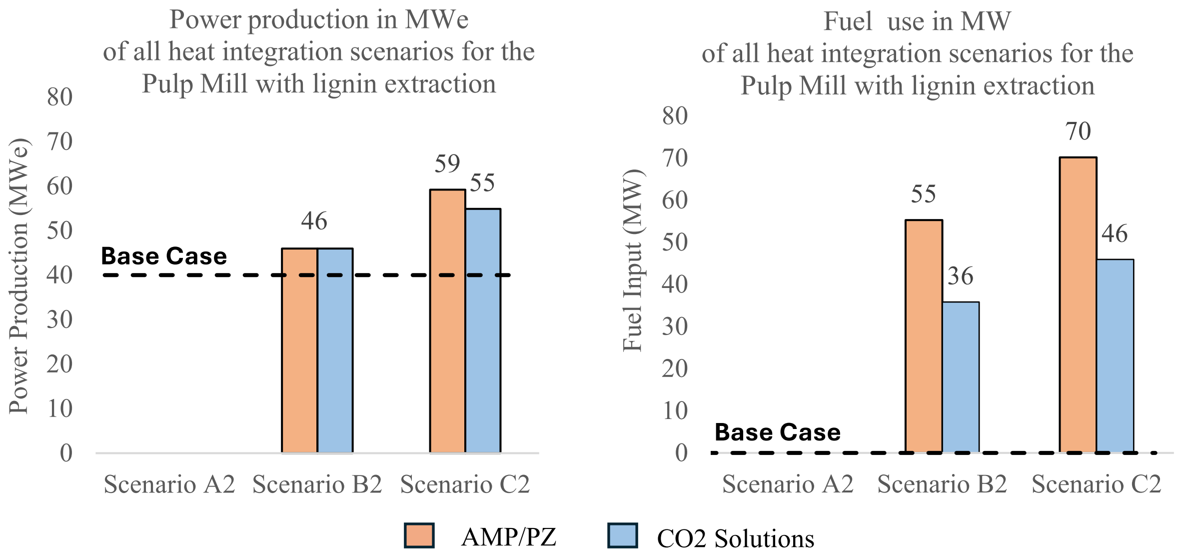

Figure 4.3: Power production (left) and fuel input (right) for the integrated system in all heat integration scenarios for the mill with lignin extraction. Scenario A2: Minimized fuel use, Scenario B2: Maximized power generation with existing turbine capacity, Scenario C2: Maximized back-pressure power generation as limited by back-pressure steam demand, but with no turbine capacity constraints. Note that the power production of the base case for lignin extraction is lower than that of the power production for the mill without lignin extraction (40 vs. 46 MWe). As for the fuel input, this is zero as there would be no need to increase fuel without carbon capture.

Similarly to the Paper Mill, hot water is produced to supply heat to the CO2 Solutions process. However, two heat exchangers are required, one using a process stream as a heat source and another using LP steam. For simplification, the heat exchanger for recovering excess heat has been sized for recovering 72% of total actual excess heat recovered as this could be met by a single process stream. The specifications of the two heat exchangers are shown in Table 4.3, where the specifications for the heat exchanger for flue gas cooling has also been included. The flue gas cooler will be part of the capital cost for both technologies.

Table 4.3: HX specifications for excess heat recovery for the Pulp Mill

	HX Area (m^2)	Hot side	Cost (M€)
HX1 – CO2 Solutions	387.6	LP steam	0.26
HX2 – CO2 Solutions	484.8	Process Heat	0.29
HXFG – Flue gas cooler	381.6	Flue gas	0.75

4.2 Capture Cost

4.2.1 Impact of site differences

Figure 4.4 shows the estimated capture cost for the AMP/PZ process when integrated with each of the studied mills. Although some care should be taken when comparing absolute numbers due to differences in heat integration methodologies (a more theoretical approach taken for the Pulp Mill), it is apparent that site differences have a significant impact on the cost of capture. This can be seen, for example, by looking at the size of specific cost components.

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Variable OPEX for electricity (which covers electricity demand as well as loss in electricity generation) makes up the largest share of the capture cost for the AMP/PZ process for both sites. For the Pulp Mill (Scenario A1), however, this cost is considerably smaller, contributing 12.5 €/tonCO_2 to the capture cost compared to 21.4 €/tonCO_2 for the Paper Mill (41% decrease). This is partly because the energy balance of the Pulp Mill is assumed to be more favourable for implementing carbon capture. Specifically, the energy balance is more favourable as maximum internal heat recovery was assumed when performing the heat integration, resulting in greater LP steam availability for capture. In addition, the impact of site differences, specifically geographical location, also contribute to a lower share in variable OPEX for electricity, as the price of electricity is lower in Sweden compared to Belgium.

Site differences play a role in other aspects of the capture cost, such as the share of CAPEX for the capture and conditioning plant (and thereby fixed OPEX). This can be attributed to one of the most apparent differences between the two mills, which is the amount of CO_2 captured. The results show a clearly lower specific CAPEX for the Pulp Mill thus demonstrating the effect of economies of scale.

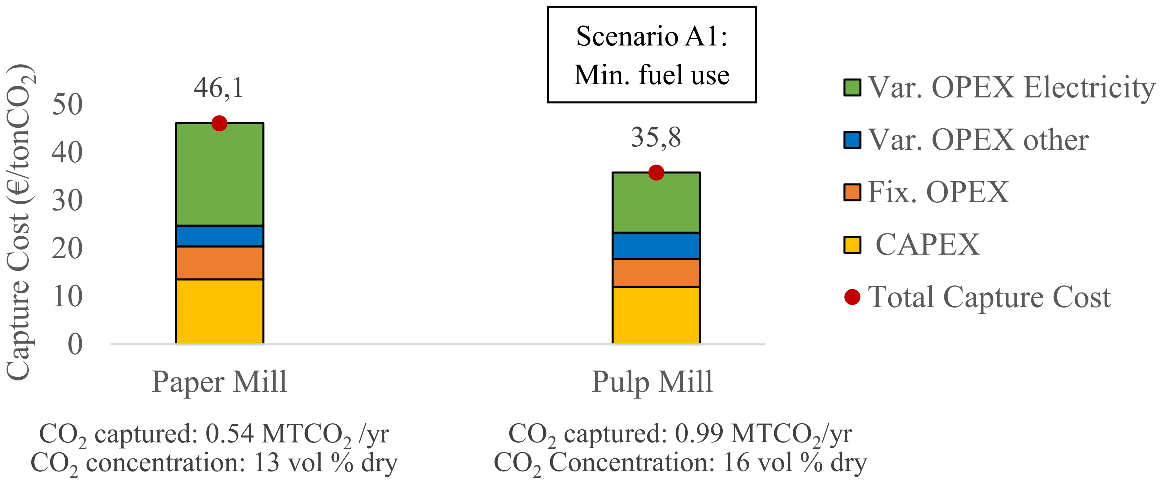

Figure 4.4: Breakdown of capture cost of the AMP/PZ process for Paper Mill (left) and Pulp Mill (right) where the electricity is priced at approximately 80 €/MWh for the Paper Mill and 50 €/MWh for the Pulp Mill. Var. OPEX electricity includes the loss in electricity generation due to the use of LP steam and the electricity demand for capture and conditioning. Var. OPEX other includes materials such as process water, solvent, and cooling water. The conditioning plant is included in the CAPEX and OPEX.

The economic performance of the AMP/PZ process should not be directly compared to the performance of the CO2 Solutions process as energy requirements and capital costs were obtained from different sources, which might not be consistent in modelling assumptions. However, it is interesting to evaluate how the characteristics of the technologies affect the impact site differences can have on the capture cost. Notably, the influence of low-temperature excess heat availability on the economic performance of the CO2 Solutions process can be observed when comparing the cost of variable OPEX electricity of the two sites.

Unlike the Paper Mill, there is low-temperature process heat available in the Pulp Mill which can be used to meet part of the reboiler heat demand for the CO2 Solutions process. As a result, the

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decrease in the share of the cost of variable OPEX electricity between the two sites is even larger. An approximate 64% decrease can be observed (from 27 €/tonCO_2 to 10 €/tonCO_2) for the CO2 Solutions process (see Figure 4.5), compared to the 41% decrease observed for the AMP/PZ process (see Figure 4.4). With regards to the other components of the capture cost, the same trend can be observed where the share of the specific CAPEX and fixed OPEX cost is lower in the Pulp Mill due to economies of scale.

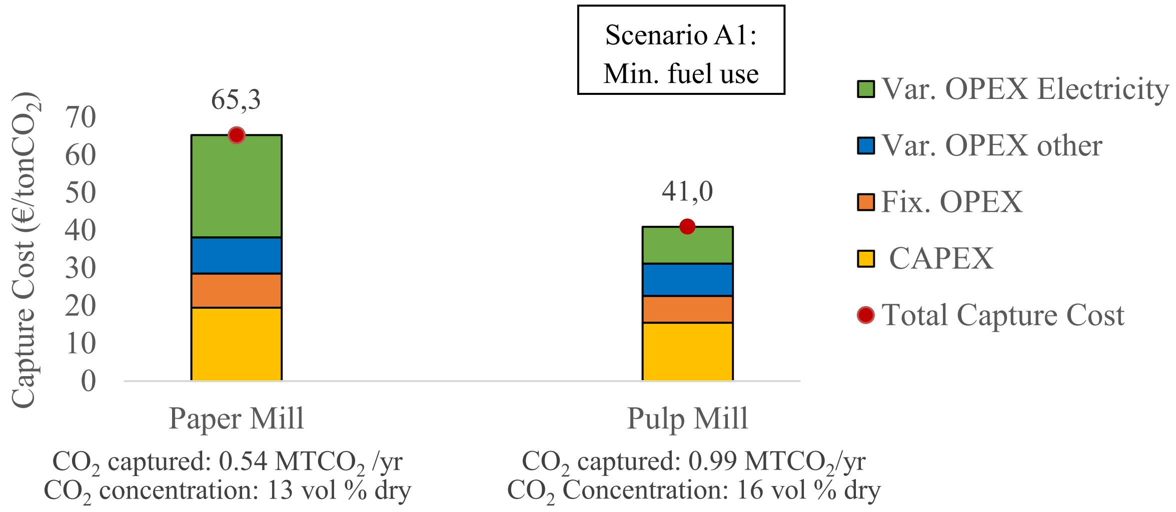

Figure 4.5: Breakdown of the capture cost of the CO2 Solutions process for the Paper Mill (left) and Pulp Mill (right) where the electricity is priced at approximately 80 €/MWh for the Paper Mill and 50 €/MWh for the Pulp Mill. Var. OPEX electricity includes the loss in electricity generation due to the use of LP steam and the electricity demand for capture and conditioning. Var. OPEX other includes materials such as process water, solvent, and cooling water. The conditioning plant is included in the CAPEX and OPEX.

4.2.2 Impact of heat integration scenarios

The breakdown of the capture cost of the AMP/PZ process for the heat integration scenarios are shown in Figure 4.6 for the Pulp Mill without lignin extraction. In Scenario B1 and C1, it can be observed that there are two additional cost components in the capture cost. For Scenario B1, there is an additional CAPEX investment (shown in grey) for a biomass boiler with a corresponding variable OPEX fuel cost (shown in dark blue). For Scenario C1, the share of these two specific cost components is even larger. Not only because the load of the biomass boiler is larger but also because of the investment in additional back-pressure turbine capacity. Note that the mill is not assumed to have any spare capacity in existing biomass boilers. In many mills, however, it can be expected that there is some capacity available to increase the load in the existing boiler and thereby avoid additional CAPEX.

Another notable difference between Scenario B1 and C1 is the share of the specific cost in variable OPEX electricity. The gain in electricity production in Scenario C1 is greater than the electricity required for capture and conditioning, resulting in a negative specific variable OPEX electricity cost. Despite these additional investments, the capture cost of Scenario B1 and C1 are only slightly larger than the capture cost of Scenario A1, indicating that the scenarios perform similarly in a low electricity price market.

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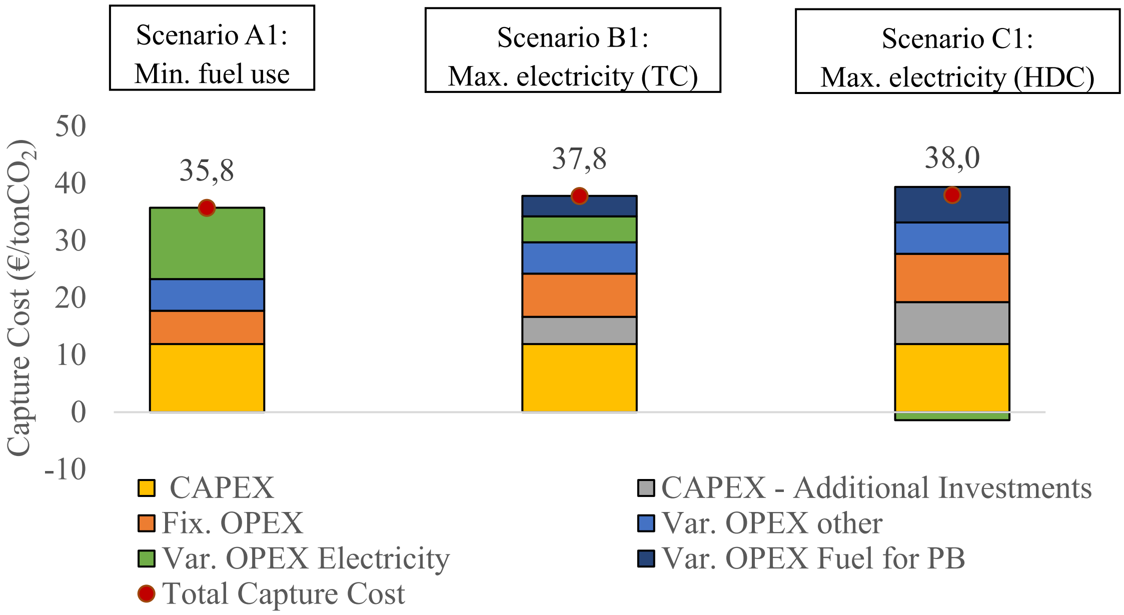

Figure 4.6: AMP/PZ process: breakdown of capture cost of the different heat integration scenarios for the Pulp Mill where the Var. OPEX other includes the cost of materials (process water and solvent) and cooling water. Note that variable OPEX for electricity is negative in Scenario C1.

The breakdown of the capture cost of the CO2 Solutions process for the different heat integration scenarios is shown in Figure 4.7. The use of low-temperature excess heat minimizes the need for a utility boiler and therefore the specific additional CAPEX investment and variable OPEX fuel cost is smaller than what was observed for the AMP/PZ process (Figure 4.6 above). As for Scenario C1, the electricity gained from maximizing back-pressure power is not enough to cover the electricity demand for capture and conditioning. What contributes the most to the cost of variable OPEX electricity is the capture technology's own electricity demand. This can be, in part, explained by the sub-atmospheric operating pressure of the stripper column, resulting in the need for an additional compression stage to 1 bar(g) to achieve the same exit conditions as the CO_2 captured by the AMP/PZ process.

It is worth noting as well that, although the costs of the two technologies should not be directly compared as their energy requirements (cooling, electricity and reboiler heat) and total direct costs were obtained following different simulation methodologies, it can be observed that they both perform similarly under the low electricity price assumptions used here. In fact, the estimated capture cost for the CO2 Solutions technology is only about 20% higher despite the more industrially relevant assumptions used compared to the theoretical model used for the AMP/PZ process. This difference should be considered very small in comparison to the uncertainties in the analysis.

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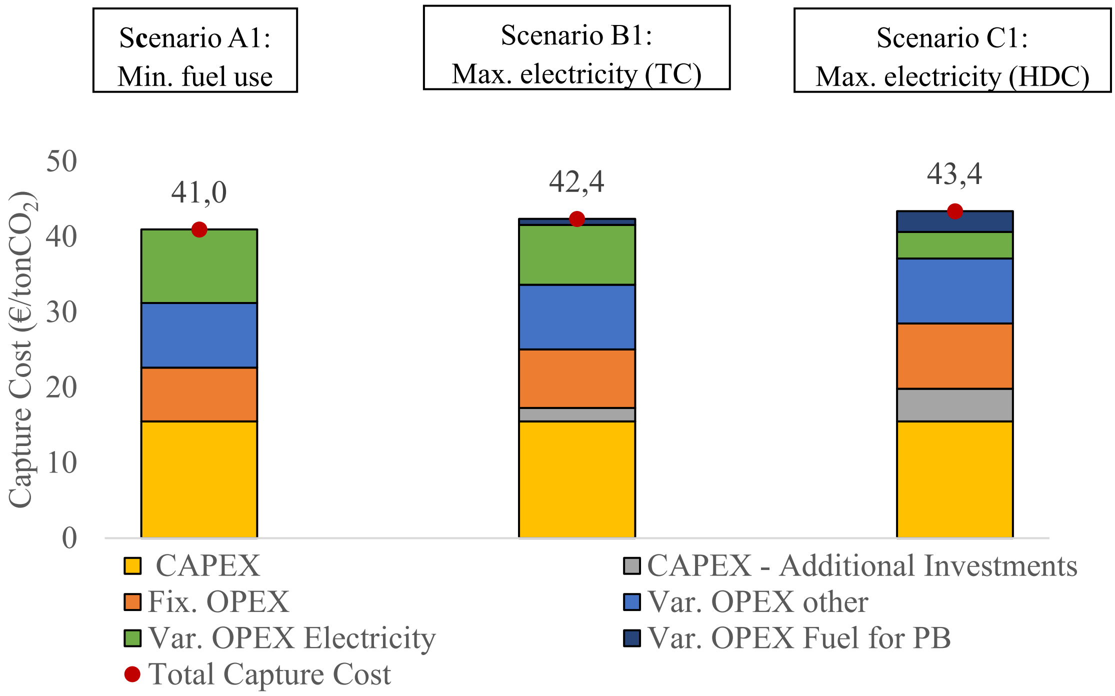

Figure 4.7: CO2 Solutions process: breakdown of capture cost different heat integration scenarios for the Pulp Mill where the Var. OPEX other includes the cost of materials (process water and solvent) and cooling water.

For the Pulp Mill with lignin extraction, the capture cost for the different heat integration scenarios was only evaluated for the AMP/PZ process. As shown in Figure 4.8, the capture cost increased by approximately 10 €/tonCO_2 for all the scenarios. This increase can be explained by the reduction in high-temperature excess heat from the recovery boilers, in turn creating a less favourable energy balance for heat integration with carbon capture. As was shown in Figure 4.3, this results in a complete loss in electricity generation and therefore, the specific cost for variable OPEX electricity is much larger in Scenario A2 compared to Scenario A1. Consequently, this also results in a higher biomass load required in Scenario B2 and C2, as shown by the larger specific cost for additional CAPEX investments and variable OPEX fuel.

While it costs more to capture CO_2 for the Pulp Mill with lignin extraction compared to the Pulp Mill without lignin extraction, it is worth noting that the analysis does not consider the economic value of lignin extraction nor the potential climate benefit of substitution effects from lignin products. The results simply illustrate that the cost of carbon capture implementation is clearly favoured by favourable mill energy balances.

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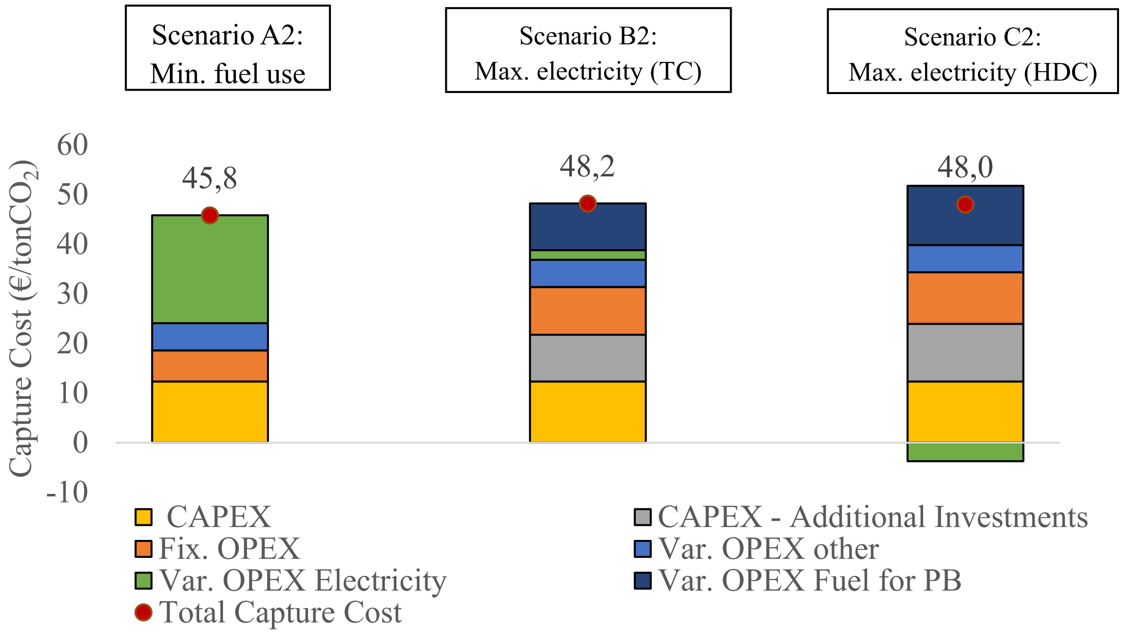

Figure 4.8: AMP/PZ process: breakdown of capture cost for different heat integration scenarios in a Pulp Mill with lignin extraction. Note that variable OPEX for electricity is negative in Scenario C2

4.2.3 Impact of Heat Pump Integration on Economic Performance of AMP/PZ Capture Process

To evaluate the economic performance of investing in an MVR heat pump, a simplified analysis was performed where the economic benefit of the heat pump was estimated based on potential reductions in power generation losses or additional fuel demand. As described in Section 3.4, the effect of supplying recompressed flash steam to cover part of the reboiler duty will differ between heat integration scenarios, that is, whether minimized fuel use or maximized power co-generation is prioritized.

As shown in Figure 4.9, the use of (ca 30 MW) recompressed flash steam instead of by-passing the turbines, makes it possible to avoid the entire loss in electricity generation in Scenario A1. Correspondingly, in Scenario B1, the heat pump could make it possible to completely avoid the additional fuel input investment in additional boiler capacity while still maximizing the utilization of the existing turbine capacity. Since the heat pump capacity can be large enough to completely avoid additional fuel use as well as losses in power co-generation, Scenario C1 with a heat pump would result in the same fuel and electricity balances as Scenario A1 and B1 and is not further analysed here.

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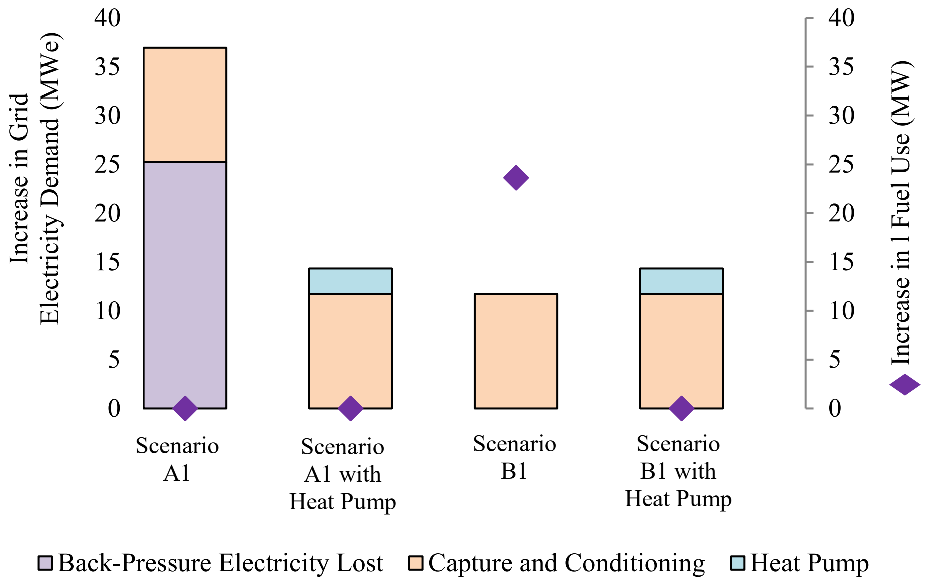

Figure 4.9: Effect on electricity and fuel demands of integrating a heat pump with the mill and the AMP/PZ capture process.

Table 4.4 summarizes the costs for the heat pump investment and operation and the effect on other costs for the mill and capture plant. Note that the targets shown in Figure 4.9, which are used to estimate the effects on operating costs, could have been reached by an MVR with a smaller capacity than 30 MW. However, this was not considered in the simplified assessment of the economic performance, i.e., the size of the heat pump was not optimized to allow for a lower investment cost and electric power demand. Consequently, the economic performance of the investment is a conservative estimate.

Table 4.4: Influence on capital requirements and operating costs of investing in an MVR heat pump to supply heat to the CO_2 capture process

Estimated cost	**Value**	
Equipment and installation costs (TDC') for the MVR heat pump	3.7 MEUR	
Annualized total capital requirement (TCR) for the MVR heat pump	0.72 MEUR/yr	
Increase in annualized total capital requirement (TCR) for stripper reboilers	0.67 MEUR/yr	
Electricity demand for heat pump	0.99 MEUR/yr	
Reduction in cooling demand	0.52 MEUR/yr	
	Scenario A1	**Scenario B1**
Avoided loss in electricity generation	7.9 MEUR/yr	
Avoided biomass fuel use		3.6 MEUR/yr
Avoided investment in biomass boiler		4.9 MEUR/yr

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When all of the above costs and benefits are considered, it seems like a heat pump could be a very promising opportunity also from an economic perspective (see Table 4.5).

Table 4.5: Economic performance of integrating an MVR heat pump to supply heat to the CO_2 capture process

	Scenario A1	Scenario B1
Reduction in annual cost for capture (= net annual profit)	6.1 MEUR/yr	6.6 MEUR/yr
Reduction in capture cost	6.1 EUR/tCO2	6.6 EUR/tCO2
Percentage reduction in cost for capture & liquefaction	17 %	17 %

It is worth noting that the excess heat availability is estimated as a theoretical potential, based on the same theoretical energy targeting approach as used for the analysis of heat integration between the mill and capture processes and the steam utility system. In the present-day mill, the flash steam is used to cover other heat demands in the mill, and significant retrofits of the heat recovery system might be needed to release the heat (just like retrofits will be needed to develop the mill towards the energy-efficiency targets assumed in the heat integration scenarios assumed for the techno-economic assessment of CO_2 capture costs). This applies regardless of whether the excess heat is considered to be used directly as a heat source for the CO_2 Solutions process, or whether its temperature is to be raised in a heat pump to supply heat to the AMP/PZ capture process. However, the heat pump opportunity outlined below relies on the specific use of flash steam, while the direct use of excess heat for the CO_2 Solutions process could use a heat collection system of various process heat sources.

Overall, the results of the simplified analysis indicate the relevance of conducting a deeper analysis of the feasibility of applying a heat pump for supplying heat to the AMP/PZ process. Such analysis should investigate the cost for making the flash steam available as an excess heat source, identify potential technologies for the MVR steam compressor and aim to provide better estimates for the cost of such a solution, provide new design and cost estimates for the stripper reboilers, and optimize the size of the heat pump.

4.2.4 Impact of varying energy market conditions

The influence of electricity and fuel price on the capture cost for the AMP/PZ process for the two pulp mills (with and without lignin extraction) can be observed in Figure 4.10. Focusing first on the Pulp Mill without lignin extraction shown on the right, it can be observed that Scenario A1 is quite sensitive to changes in electricity price compared to other scenarios, as indicated by its slope. This is to be expected, given that in this scenario, the mill has lost almost half of its electricity production. Above an electricity price of approximately 80 €/MWh, the economic performance of all three scenarios is no longer comparable. When the price of electricity is high, it becomes worthwhile to invest in a biomass boiler to meet the heat demand of the capture process and maintain power production (Scenario B1). For Scenario C1, the capture cost decreases with an increasing price for electricity, achieving the lowest capture cost among the scenarios at approximately 60 €/MWh and above. The decreasing trend is due to the additional gain in electricity production, which resulted in a negative specific variable OPEX electricity cost (see Figure 4.6).

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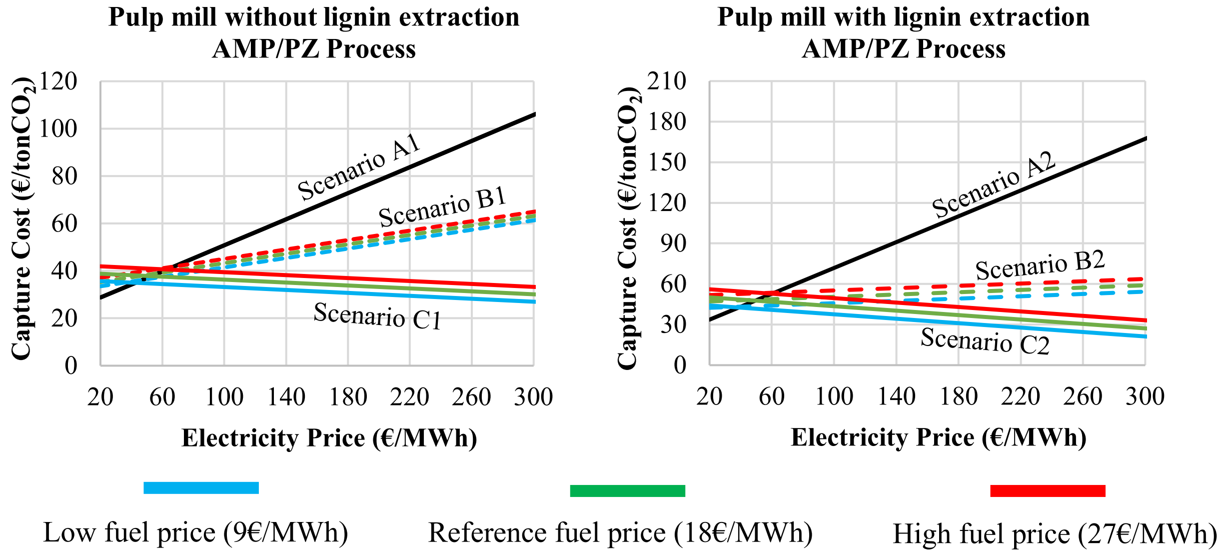

Figure 4.10: Sensitivity analysis on electricity and fuel prices for the capture cost of the AMP/PZ process, where Scenario A (shown in black) is unaffected by changes in fuel prices since there is no additional fuel use. Recall that Scenario A is when fuel use is minimized, Scenario B (dotted lines) is when electricity generation is maximized but constrained by existing turbine capacity and Scenario C is when (back-pressure) electricity is maximized but constrained based on the minimum heat demand.

Similar trends can be observed for the Pulp Mill with lignin extraction, shown on the right of Figure 4.10. Since all the electricity production is lost, Scenario A2 has higher sensitivity to variation in electricity price compared to Scenario A1. With or without lignin extraction, the capture cost of the AMP/PZ process appears to be minimally affected by changes in fuel price compared to changes in electricity price. The mill with lignin extraction is, however, less affected by changes in electricity price when back-pressure power generation is maximized within existing turbine capacity limits (compare Scenario B2 to Scenario B1). This is because the mill with lignin extraction would have a 6 MWe lower electricity generation potential before the integration of the capture plant, which creates a larger potential to increase back-pressure power generation against the new steam demand from the capture plant, thereby better balancing increased power generation against the electricity demand for capture.

What can also be observed in Figure 4.10 is that the capture cost of the AMP/PZ process appears to be affected minimally by changes in fuel price compared to changes in electricity price. This is seen by the proximity of the three different fuel price lines where red is a high fuel price, green is the reference fuel price and blue is a low fuel price. The fuel price was not varied as much as the electricity price, however comparing the impact that the same variation (+/- 50%) has on the capture cost confirms that the electricity price is indeed more influential. For example, in Scenario B1, going from 120 €/MWh to 180 €/MWh, the capture cost increases approximately by 5 €/tonCO_2. The capture cost from the reference fuel price to a higher fuel price result in less than 1 €/tonCO_2 increase. A higher dependency on fuel price can be observed in Scenario C (shown by the larger gap between the different fuel prices), which is to be expected given that this scenario has a larger additional fuel consumption compared to Scenario B.

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The influence of energy market conditions on the heat integration scenarios for the CO2 Solutions process was also explored, as shown in Figure 4.11. All scenarios appear to be quite sensitive to variations in electricity price, as indicated by their slope. Scenario A1 and B1 perform quite similarly with B1 only achieving a slightly lower capture cost at electricity prices around 100 €/MWh and above. This can be explained by the balance between what is lost in electricity generation (due to LP steam use) and what the capture technology consumes, where the latter is greater. Consequently, Scenario C1 performs the best in a high electricity price market (≈ 80 €/MWh and above) as the additional gain in electricity can be used to meet part of the electricity demand for capture and conditioning.

Due to the minimal loss in electricity generation (and thereby less additional fuel consumption), compared to the AMP/PZ process, the heat integration scenarios for the CO2 Solutions process are even less influenced by variations in fuel price. This can be observed by comparing the proximity of the fuel price lines.

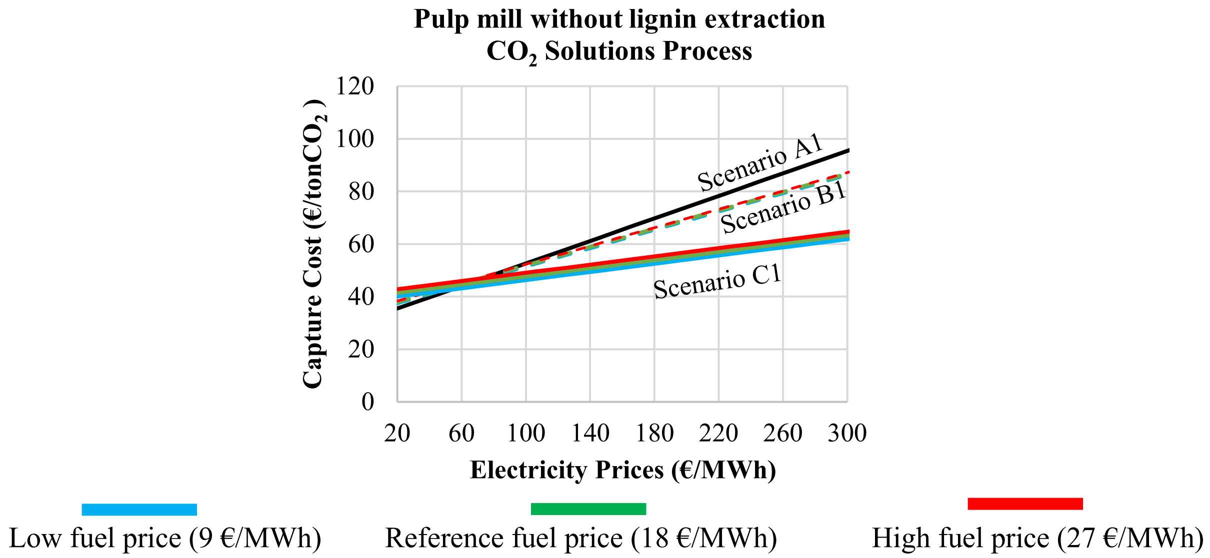

Figure 4.11: Sensitivity analysis on electricity and fuel prices for capture cost of the CO2 Solutions process, where Scenario A1 (shown in black) is unaffected by changes in fuel prices since there is no additional fuel use. Scenario A1 is when fuel use is minimized, Scenario B1 is when electricity generation is maximised with constraints on turbine capacity and Scenario C1 is when electricity is maximized with constraints based on heat demand.

4.3 CO_2 Emissions after Integration

The remaining CO_2 emissions after the implementation of carbon capture in the Paper Mill and the two pulp mills (with and without lignin extraction) is detailed in Figure 4.12. What sets the heat integration scenarios apart are the additional biogenic emissions from the biomass boiler and the indirect (fossil) emissions from the change in electricity production. In Scenario A, indirect fossil fuel emissions from the grid are the highest. In Scenario C, biogenic emissions are the largest, and correspondingly indirect fossil emissions are the smallest. This scenario also happens to be the most economically feasible when the price of electricity is above approximately 60 €/MWh (from Figure 4.10).

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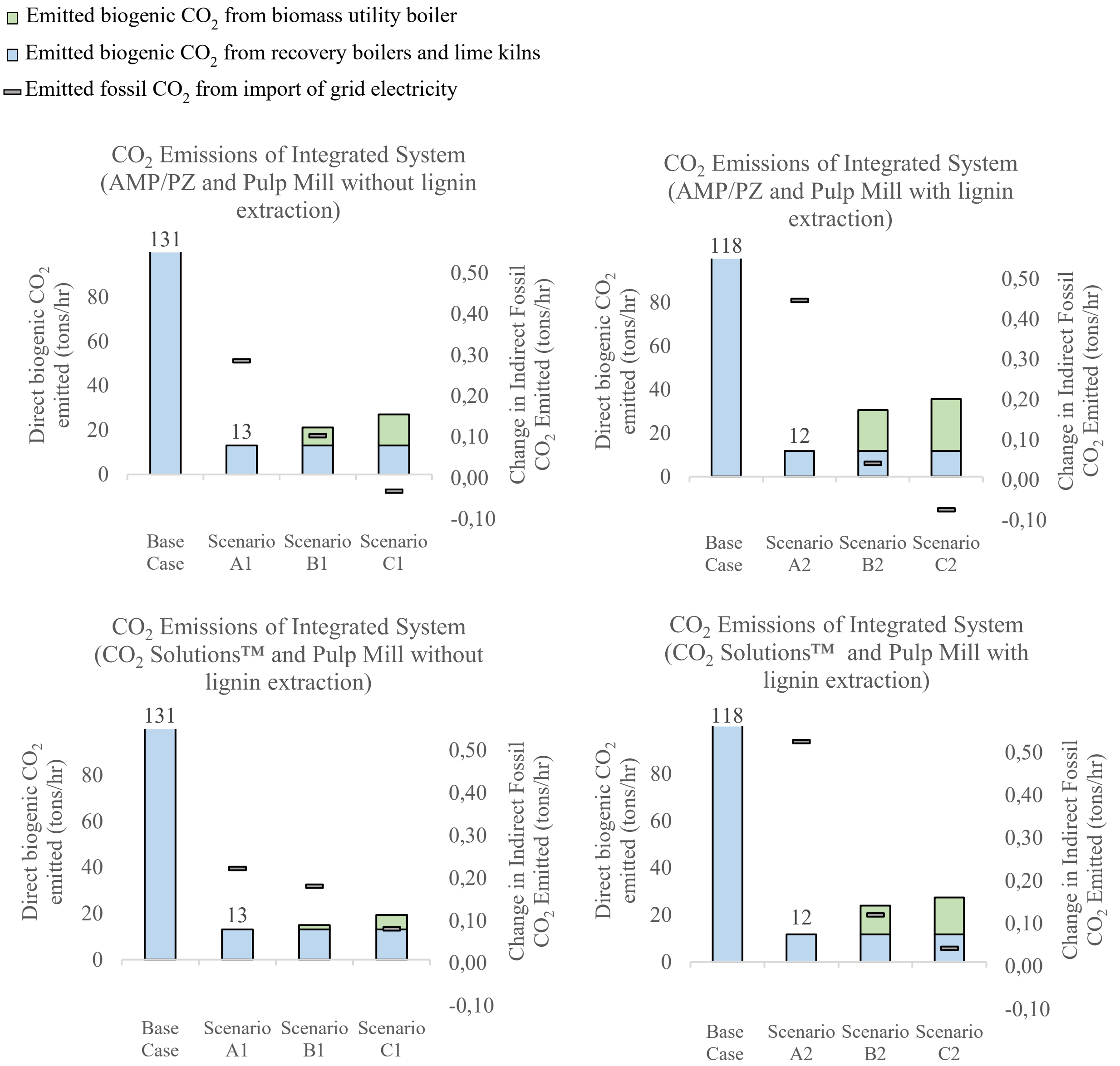

Figure 4.12: Resulting CO_2 emissions (in ton/hr) from integrating the Pulp Mill (with and without lignin extraction) with the AMP/PZ process (top) and CO2 Solutions process (bottom). Note that the emitted CO_2 from recovery boilers and lime kilns go beyond the scale of the graph for the base case, and that the change in indirect fossil CO_2 emissions is relative to the base case. In the case of Scenario C, the additional electricity produced would reduce the need to import electricity from the grid, thereby leading to a decrease in indirect fossil emissions (shown as negative for the AMP/PZ process).

The total CO_2 emissions of the Pulp Mill with lignin extraction are lower than without lignin extraction (see base case biogenic emissions in Figure 4.12) as more carbon from the feedstock is converted into a product (lignin). Less CO_2 is therefore captured by the capture plant but the overall CO_2 emissions with capture are lower than for the Pulp Mill without lignin extraction (comparing Scenario A1 to A2). However, this effect is negated when comparing Scenario B and C, as there is a greater demand for the biomass boiler (therefore greater CO_2 emissions) due to the unfavourable energy balance of the mill.

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The emissions from electricity in the Pulp Mill are estimated based on yearly electricity production and annual average CO_2 intensity of grid electricity (for Sweden). Consequently, this does not take into consideration marginal effects on electricity generation in the grid. The CO_2 intensity of grid electricity varies between countries and regions, making it difficult to state that one scenario is better than the other when comparing their net CO_2 emissions after capture. Indeed, whether it is better to accept the loss in electricity or to utilize more biomass to restore power generation is very much dependent on the system in which the mill operates. It could be argued that in countries where coal is on the margin, it would be better to restore power generation as it would avoid increasing indirect fossil fuel emissions, at the cost of emitting biogenic CO_2. On the other hand, as countries move towards a decarbonized economy, an emissions intensity like Sweden is likely to be representative of many European countries in the future, and therefore the argument for avoiding indirect fossil emissions from the grid will no longer be fully valid.

It is also important to consider substitution effects, where the additional use of biomass resources for electricity production would prevent it from being used for other applications such as production of biofuels or bio-based products. Another key aspect to consider is the amount of additional biomass available that could be consumed by the mill, something that also may be limited by an increased used of biomass for new applications, but also depends on the region where the mill is located. Specifically in Sweden, (Karlsson et al., 2021) found that the Bio-energy Carbon Capture and Storage (BECCS) potential in the Swedish pulp and paper industry would be limited in regions where there is competition for logging residues. An important takeaway here is that the implementation of carbon capture not only affects the mill's operation, but also the system in which the mill operates.

This effect of emissions intensity can be observed when comparing the emissions of the Paper mill with carbon capture to that of Scenario A1 for the Pulp Mill, see Table 4.6. The electricity required includes what was lost in electricity generation due to LP steam consumption and the electricity demand of the capture and conditioning plant.

Table 4.6: Comparing CO_2 emissions (kg/hr) from the electricity required from the grid after integrating carbon capture in the Pulp Mill and the Paper Mill. The Paper Mill is in Belgium (assumed electricity emissions intensity of 230.70 $kgCO_2/MWh$) and the Pulp Mill is in Sweden (assumed electricity emissions intensity of 8.0 $kgCO_2/MWh$).

		Paper Mill	Scenario A1 (Pulp Mill)
Electricity required from the grid (MW)	AMP/PZ	19	33
	CO2 Solutions	24	25
$CO_{2\,\Delta\,electricity}$ (fossil)	AMP/PZ	4,382	286
	CO2 Solutions	5,573	222

4.4 Avoidance Cost

The capture cost was selected as the main economic key performance indicator of the TEA instead of the avoidance cost due to uncertainty in indirect emissions from other activities in the bio-CCS value chain, such as the activities before and after the mill (e.g. wood harvesting and transportation, CO_2 transport and leakages), as well as the cost uncertainty of future transportation and storage infrastructure. Calculating the CO_2 avoidance cost would therefore require making additional assumptions, adding another layer of uncertainty to the reported cost. In addition, given that the aim of this study is to obtain a general understanding of the capture cost for pulp and paper mills in Europe, the cost of transportation will vary significantly depending on the site-location.

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The capture cost is deemed appropriate for evaluating the cost efficiency of a capture technology, but for a better representation of the cost of achieving negative emissions, one should evaluate the cost of CO_2 avoided.

As the indirect fossil emissions from the electricity consumption of each heat integration scenario are known (see Figure 4.12), a simplified avoidance cost can be estimated, which considers the indirect emissions associated with capture, but neglects costs (and emissions) associated with transport and storage. Here, we refer to this as a *quasi*-CO_2 avoidance cost, which can be calculated by subtracting these indirect (fossil) emissions from the total amount of CO_2 captured. In comparison, the *real* CO_2 avoidance cost would consider the cost of transportation and storage, and the emissions from transportation (upstream and downstream of the mill), in addition to the indirect emissions from the import of electricity to the mill and capture site. The difference between the capture cost, *quasi*-CO_2 avoidance cost and *real*-CO_2 avoidance cost is shown in Figure 4.13.

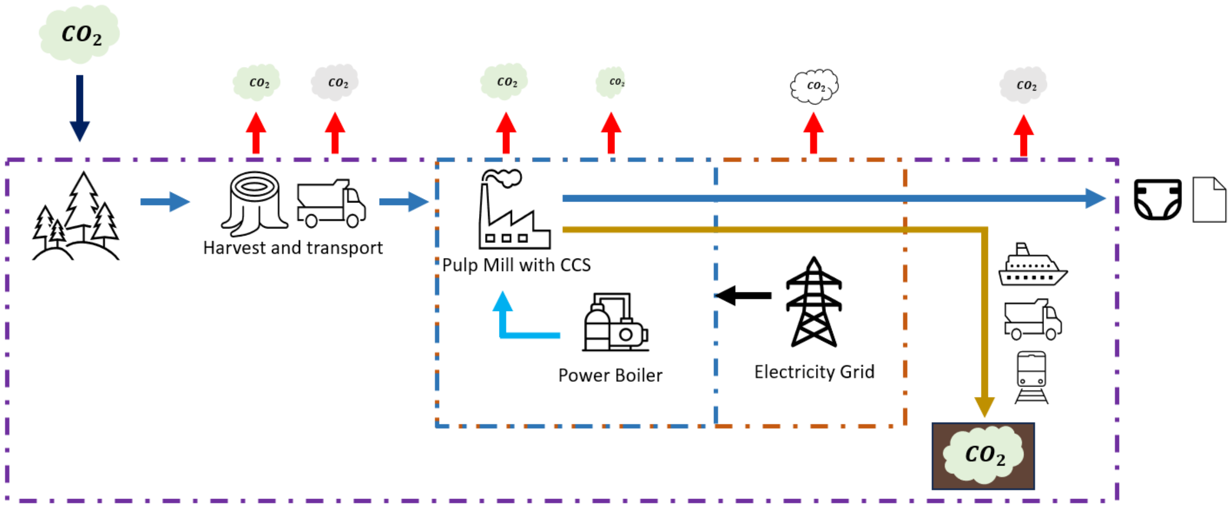

Figure 4.13: Simplified schematic of the CCS chain for the Pulp Mill. Enclosed in the purple dashed box signifies the activities included when evaluating the CO_2 avoidance cost. Enclosed in the orange dashed box is what is included in the quasi- CO_2 avoidance cost reported in this work and lastly enclosed in the blue dashed box is what is included in the capture cost. (Icons from www.flaticons.com)

The calculated *quasi*-CO_2 avoidance cost of the AMP/PZ process and how it compares to the capture cost reported in Section 4.2 is shown in Table 4.7. Note that the real CO_2 avoidance cost would be greater than what is reported in Table 4.7.

Table 4.7: Quasi-CO_2 avoidance cost (€/tonsCO_2) of the AMP/PZ process for the Pulp Mill where the indirect fossil emissions from the import of electricity has been subtracted from the total biogenic emissions captured. Note that in Scenario C1, the capture cost and quasi-CO_2 avoidance cost are equal as there is no need import electricity to meet the demand for capture and conditioning.

	Capture Cost	Quasi-CO_2 Avoidance cost
Scenario A1	35.78	35.87
Scenario B1	37.85	37.88
Scenario C1	38.01	38.01

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5 DISCUSSION AND SUGGESTIONS FOR FURTHER WORK

5.1 Flexible Operation

For the AMP/PZ process, the results of the sensitivity analysis on electricity and fuel prices indicates there is a potential for flexible operation between heat integration scenarios, see Figure 4.8. For example, a mill owner could choose to maximize power generation in their existing turbines (corresponding to operation in Scenario B) when the price of electricity is high and to minimize fuel use (corresponding to operation in Scenario A) when the price of electricity is low. Although investment in new turbines for even higher power generation (corresponding to Scenario C) could provide a lower capture cost in a market with consistently high electricity prices, such a scenario carries a greater investment risk. If the price of biomass were to increase significantly, the pulp mill owner would likely cease the operation of the additional biomass boiler and turbine, resulting in a greater number of stranded assets compared to the other scenarios. The results of the sensitivity analysis for the CO2 Solutions process further indicate that such flexibility is only feasible if the performance of the capture technology differs significantly between heat integration scenarios.

For a pulp mill with lignin extraction, one could potentially investigate flexible lignin extraction based on excess heat availability. For example, when the mill's process heat demand is high, such as in the winter months, the lignin extraction rate could be reduced to minimize the cost of capture. Alternatively, one could optimize lignin extraction based on the energy market such that when the price of electricity is high, the lignin extraction rate could be reduced to minimize the losses in electricity generation. The future willingness to pay for biogenic CO_2, whether this is from a demand for negative emissions or from a carbon capture and utilisation (CCU) market such as for electrofuels, will be in large part be the deciding factor on whether to implement carbon capture or lignin extraction. As market demand for both are currently uncertain, it will be interesting to see how they compare in the future.

As for mills with unfavourable energy balances, such as integrated pulp and paper mills, partial capture may be a more cost-effective option. Biermann et al. studied partial carbon capture by absorption and found that, depending on the market conditions, lower specific costs (€ per tonne of CO_2 captured) could be achieved compared to full capture (Biermann et al., 2018).Whether this would indeed be the case for integrated pulp and paper mills would need to be further explored.

5.2 Methodology Limitations

Several assumptions and simplifications were made when completing the techno-economic assessment (TEA), resulting in uncertainty in the capture costs reported in this work. In the whitepaper for improved CCS cost estimation (IEAGHG, 2021), the authors state that a bottom-up cost engineering approach, such as the one followed in this work, cannot provide an accurate prediction for the expected future cost of a carbon capture technology which has not yet reached commercial availability. This is the case for both the AMP/PZ and CO2 Solutions process. It is worth noting that the low technological maturity also introduces uncertainty in the energy requirements as they were obtained from modelling and simulations rather than real operational data. The economic assessment performed also did not consider the full cost for heat recovery, nor site specific costs such as cost of retrofitability (i.e. flue gas piping) and spatial constraints. As quantified by (Roshan Kumar, 2024.), foregoing the cost of retrofitability and spatial constrains introduces a considerable degree of uncertainty in the final cost estimates.

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The last degree of uncertainty from the methodology comes from the use of a pinch-based energy targeting approach for evaluating the heat integration potential between the capture technologies and the Pulp Mill. Specifically, the amount of high- and low-temperature excess heat available to meet part of the capture heat demand of the CO2 Solutions process is uncertain as it was obtained using a theoretical approach. Given that the results in this work indicate this is a key parameter for achieving cost-effective carbon capture, how much excess heat is actually available for recovery in a pulp mill should be further investigated. Bearing all these uncertainties in mind, the reader should therefore not focus on the absolute numbers reported in the present work as they are likely to be optimistic estimates.

5.3 Bio-CCS Beyond Site Level

This work focused on the impacts that carbon capture has on the pulp and paper industry at a site-level where the impacts outside this boundary were not addressed in detail. Namely, challenges which could limit or prevent the implementation of bio-CCS such as the absence of policy or other financial incentives (e.g. voluntary markets for carbon removal credit) have not been addressed in this work.

The exact cost of implementing carbon capture in the pulp and paper industry may be uncertain but it is certain that a mill owner will incur a cost. Without financial incentives for carbon removals or biogenic carbon pricing, such an implementation is unlikely to occur. It would be interesting to explore in future work what carbon removal credit price would make bio-CCS profitable. In addition, one could also explore whether policy could have an influence on how carbon capture should be implemented in a Pulp Mill. For example, which heat integration scenario would be best if the pulp mill owner wants to obtain carbon removal credits for capturing biogenic CO_2? Although all scenarios capture the same amount of CO_2, any on-site biogenic CO_2 emissions that are not captured or indirect emissions of fossil CO_2 due to increased demand for grid electricity, could reduce the total negative emissions the pulp mill owner could claim. In addition to lack of policy, there are other barriers to deployment of bio-CCS in the pulp and paper industry in Europe such as biomass availability, social acceptance, cost, and availability of infrastructure for CO_2 transport and storage. Addressing these challenges was not the focus of this work package.

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6 CONCLUSIONS

In this work, a techno-economic assessment was performed to estimate the CO_2 capture cost for two different post-combustion CO_2 capture technologies installed at a Paper Mill and a Pulp Mill. The two capture technologies explored were an amine-based post-combustion capture (PCC) technology (using AMP/PZ as a solvent) and a carbonate-based technology (CO2 Solutions). The impact of possible future strategic developments to improve utilisation of the biomass feedstock on the implementation of carbon capture was investigated by evaluating the capture cost for a Pulp Mill with lignin extraction. The estimated capture costs are uncertain and not directly comparable between mills and technologies due to differences in cost estimation methodology and assumptions. Accordingly, the main conclusions listed below focus on qualitative aspects:

1) **Site-specific factors have a strong impact on the capture cost**. Specifically, the flue gas flowrate (and its CO_2 concentration), the site location and the mill's energy balance all have a significant impact on the capture cost. This makes it difficult to generalize results from one specific mill to other mills, since accurate cost estimates for carbon capture must consider site-specific factors.
2) **The way in which carbon capture is integrated at a site and the energy system in which the site operates have a significant impact on the capture cost**. When electricity prices are low, the lowest capture cost is achieved when fuel use is minimized, but this also results in the highest indirect fossil fuel emissions from the grid. At high electricity prices, the lowest capture cost is achieved when back-pressure power generation is maximized, but this results in the highest biogenic CO_2 emissions from an additional biomass boiler. This is the case for both capture technologies. A pulp mill owner could potentially choose to minimize fuel use when the electricity price is low and maximize power co-generation when the price is high to reduce the capture cost. However, while this would reduce operating costs, the capacity factor for the biomass boiler would be lower, therefore leading to higher specific capital costs.
3) **CO_2 capture technologies, such as the CO2 Solutions process studied in this work, that can utilize low-temperature excess process heat will have a reduced need for additional firing of the site utility boiler to avoid losses in co-generation of electricity**. For such technologies, excess heat availability is an important parameter for achieving a lower capture cost.
4) **If a heat pump can be used, availability of low-temperature excess heat can also be an advantage for capture technologies where the reboiler requires higher temperatures**. The cost of investing in and operating an MVR heat pump with a limited temperature lift seems to be well compensated by the potential operating cost reduction associated with the resulting lower use of utility steam.
5) **The expected capture cost of the Pulp Mill with lignin extraction is higher than the capture cost for the Pulp Mill without lignin extraction**. However, this is only an indication that carbon capture implementation is clearly favoured by favourable mill energy balances.

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7 REFERENCES

Becattini, V., Riboldi, L., Burger, J., Nöhl, J., Oeuvray, P., Reyes-Lúa, A., Anantharaman, R., Bardow, A., Frattini, L., Fu, C., Mazzotti, M., Roussanaly, S., & Zotică, C. (2024). Rolling-out pioneering carbon dioxide capture and transport chains from inland European industrial facilities: A techno-economic, environmental, and regulatory evaluation. *Renewable and Sustainable Energy Reviews*, *205*, 114803. https://doi.org/10.1016/J.RSER.2024.114803

Beiron, J., & Johnsson, F. (2024). Progressing from first-of. *International Journal of Greenhouse Gas Control*, *137*, 104226. https://doi.org/10.1016/j.ijggc.2024.104226

Biermann, M., Normann, F., Johnsson, F., & Skagestad, R. (2018). Partial Carbon Capture by Absorption Cycle for Reduced Specific Capture Cost. *Industrial and Engineering Chemistry Research*, *57*(45), 15411–15422. https://doi.org/10.1021/ACS.IECR.8B02074

Castilla, G. M., Guío-Pérez, D. C., Papadokonstantakis, S., Johnsson, F., & Pallarès, D. (2021). Techno-Economic Assessment of Calcium Looping for Thermochemical Energy Storage with CO2 Capture. *Energies 2021, Vol. 14, Page 3211*, *14*(11), 3211. https://doi.org/10.3390/EN14113211

Demirbas, T., & Demirbas, C. (2009). Fuel properties of wood species. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *31*(16), 1464–1472. https://doi.org/10.1080/15567030802093153

Garðarsdóttir, S.O., Normann, F., Skagestad, R., & Johnsson, F. (2018). *Investment costs and CO2 reduction potential of carbon capture from industrial plants-A Swedish case study*. https://doi.org/10.1016/j.ijggc.2018.06.022

Gilassi, S., Taghavi, S. M., Rodrigue, D., & Kaliaguine, S. (2020). Techno-economic evaluation of membrane and enzymatic-absorption processes for CO2 capture from flue-gas. *Separation and Purification Technology*, *248*, 116941. https://doi.org/10.1016/J.SEPPUR.2020.116941

IEAGHG (2021). *White Paper: Towards improved guidelines for cost evaluation of carbon capture and storage*, 2021-TR05, IEAGHG, August 2021. https://ieaghg.org/publications/white-paper-towards-improved-guidelines-for-cost-evaluation-of-carbon-capture-and-storage/

Karlsson, S., Eriksson, A., Normann, F., & Johnsson, F. (2021). Large-Scale Implementation of Bioenergy With Carbon Capture and Storage in the Swedish Pulp and Paper Industry Involving Biomass Supply at the Regional Level. *Frontiers in Energy Research*, *9*. https://doi.org/10.3389/FENRG.2021.738791/

Klute, S., Budt, M., van Beek, M., & Doetsch, C. (2024). Steam generating heat pumps – Overview, classification, economics, and basic modeling principles. *Energy Conversion and Management*, *299*, 117882. https://doi.org/10.1016/J.ENCONMAN.2023.117882

Kuparinen, K., Vakkilainen, E., & Tynjälä, T. (2019). Biomass-based carbon capture and utilization in kraft pulp mills. *Mitigation and Adaptation Strategies for Global Change*, *24*(7), 1213–1230. https://doi.org/10.1007/s11027-018-9833-9

Mitigation Pathways Compatible with Long-term Goals. (2022). In *Climate Change 2022 - Mitigation of Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157926.005

Rodriguez, E., Lefvert, A., Fridahl, M., Gr, S., Onkvist, €, Haikola, S., & Hansson, A. (2020). *Tensions in the energy transition: Swedish and Finnish company perspectives on bioenergy with carbon capture and storage*. https://doi.org/10.1016/j.jclepro.2020.124527

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., & Vilariño, M.V. (2022). Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. In

This project has received funding from the European Union's Horizon2020 Research and Innovation Programme under Grant Agreement No 101022487

Global Warming of 1.5°C (pp. 93–174) [Masson-Delmotte, V., et al. (eds.)]. Cambridge University Press. https://doi.org/10.1017/9781009157940.004

Rosa, L., Sanchez, D. L., & Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy & Environmental Science*, *14*(5), 3086–3097. https://doi.org/10.1039/D1EE00642H

Roshan Kumar, T. (2024). *Decarbonization in Carbon-Intensive Industries: An Assessment Framework for Enhanced Early-Stage Identification of Optimal Decarbonization Pathways*. [Thesis for the degree of Licentiate of Engineering]. Chalmers University of Technology, Göteborg. https://research.chalmers.se/publication/540512

Roussanaly, S., Berghout, N., Fout, T., Garcia, M., Garðarsdóttir, S., Mohd Nazir, S., Ramirez, A., & Rubin, E. S. (2021a). Towards improved cost evaluation of Carbon Capture and Storage from industry. *International Journal of Greenhouse Gas Control*, *106*, 1750–5836. https://doi.org/10.1016/j.ijggc.2021.103263

Roussanaly, S., Anantharaman, R., Jordal, K., Giraldi, C., & Clapis, A. (2017). Understanding the cost of retrofitting CO_2 capture in an integrated oil refinery. SINTEF report 2017:00222. SINTEF Energy Research. https://www.sintef.no/globalassets/project/recap/d5_recap-deliverable-d5-report.pdf

Svensson, E., Morandin, M., & Harvey, S. (2019). Characterization and visualization of industrial excess heat for different levels of on-site process heat recovery. *International Journal of Energy Research*, *43*(14), 7988–8003. https://doi.org/10.1002/er.4787

Svensson, E., Skoglund, H., Fu, C., Kim, D., Vantaggiato, E., Usai, G., Lindgren, K., Reyes Lúa, A., & Harvey, S. (2023). *CO2 capture integration scenarios and process modelling (D5.2)*. https://zenodo.org/communities/accsess

Thunman, H., Gustavsson, C., Larsson, A., Gunnarsson, I., & Tengberg, F. (2019). Economic assessment of advanced biofuel production via gasification using cost data from the GoBiGas plant. *Energy Science and Engineering*, *7*(1), 217–229. https://doi.org/10.1002/ESE3.271

Towler, G., & Sinnott, R (2008). *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*. Butterworth-Heinemann. https://core.ac.uk/download/pdf/143491361.pdf

Vakkilainen, E. K., Välimäki, E., & Vakkilainen, E. (2009). *Effect of Lignin Separation to Black Liquor and Recovery Boiler Operation*. https://doi.org/10.13140/2.1.2039.6485

Välimäki, E., Niemi, P., & Haaga, K. (2010). *A Case Study on the Effects of Lignin Recovery on Recovery Boiler Operation*. https://doi.org/10.13140/2.1.1777.5046

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APPENDIX

A APPENDIX A

Due to new input data from capture simulations, as well as adjustments in assumptions and data for the mill processes and steam cycles, some of the results reported in deliverable D5.2 (Svensson et al., 2023) have been updated during the work with the techno-economic assessment in Task 5.3. The updated results are shown below in Table A.1 and Table A.2, which correspond to Table 5.7 and 5.8 in D5.2, respectively.

Table A.1: Estimated minimum utility boiler heat production and maximum potential power generation from the back-pressure steam turbine under different assumptions about the trade-off between fuel use and electricity generation (updated Table 5.7 from D5.2)

	Base Case	**Carbon Capture**	**Lignin Extraction**
Recovery Boiler Primary steam production [MW]	286	286	248
Recovery boiler high temp. excess heat [MW]	110	25.7	0
Min. hot utility requirement [MW]	0	0	0

Table A.2: Estimated minimum utility boiler heat production and maximum potential power generation from the back-pressure steam turbine under different assumptions about the trade-off between fuel use and electricity generation (updated Table 5.8 from D5.2)

		Mill without carbon capture[a]	**Carbon capture only**	**Lignin extraction and carbon capture**
Minimized Fuel Use	Utility boiler steam production (MW)	0	0	0
	BP power production (MW)	46.0	25.1	1.1
Maximized Electricity Production	Utility boiler steam production (MW)	0	36.2	47.4
	BP power production (MW)	46.0[b]	61.3	56.0

[a] Energy efficient Pulp Mill based on Skutskär with BP power production limited to existing turbine size
[b] Note that for a Pulp Mill with lignin extraction, the BP power production is smaller (40MWe)

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