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Chemical pulp mills in future energy markets with variable electricity prices and increased demand for biogenic carbon

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A B S T R A C T

In a typical chemical pulp mill, heat and electricity are generated as by-products. With increased value of biogenic carbon, however, alternative products may be more valuable. In the present study, a techno-economic optimisation model representing a pulp mill is subjected to possible near-future energy markets to compare investments in: (i) a condensing turbine for increased electricity generation; (ii) lignin extraction for biofuel production; and (iii) carbon capture for either storage or utilisation.

Under present market conditions, the model mill invests in a condensing turbine for increased electricity generation. In a scenario representing Year 2030, the condensing turbine is complemented with a lignin extraction plant, and for scenarios representing Year 2040, the mill invests also in carbon capture. When both lignin and CO_2 are priced based on the demand for sustainable fuels, lignin extraction is favoured over carbon capture (although the technical limitations of lignin extraction motivate a combination of both technologies). When instead the CO_2 price is set by the demand for negative emissions, according to an assumed price of emissions allowances in the EU ETS, lignin extraction cannot compete with carbon capture. Already at a CO_2 price of 75 €/t (The ETS credit price of 2024), the price of lignin must be over 300 €/t for the optimisation model to choose investments in lignin extraction over carbon capture. The share of green carbon atoms used for products can be improved with lignin extraction; however, for the highest potential to reduce fossil emissions in other sectors, carbon capture is required.

List of abbreviations

Abbreviation	Definition
ADT	Air-dry tonnes
BB	Bark boiler
BECCU	Bio-energy carbon capture and utilisation
BECCS	Bio-energy carbon capture and storage
CO_2	Carbon dioxide
ETS	Emission trading system
EU	European Union
LK	Lime kiln
RB	Recovery boiler

1. Introduction

The European Union (EU) is targeting net-zero greenhouse gas emissions by Year 2050 [1]. If the target and the agreed policies supporting it remain in place, new demands for biogenic carbon may appear. For example, in the maritime transport sector, a transition to biofuels and/or e-fuels will be necessary if fossil fuels are to be phased out [2]. In addition, there may be a demand for bio-energy carbon capture and storage (BECCS), to compensate for residual emissions in some so called 'hard-to-abate-sectors' or to reach net-negative emissions eventually in the overall economy [3].

Chemical pulp mills, which produce pulp from woody biomass, are currently some of the largest processors of biogenic carbon in Europe. In a typical pulp mill, only around 40 % of the carbon in the raw material ends up in the main product. The remainder of the carbon is used to generate heat and electricity, whereby it is emitted as carbon dioxide (CO_2) from the recovery boiler, bark boiler and lime kiln [4]. The surplus electricity is sold to the grid as a by-product from the mill. However, if the value of biogenic carbon increases, it may be more valuable to produce other products from the surplus energy, and several mature technologically alternatives exist. One option is to extract lignin from the black liquor to be subsequently refined into biofuels or bio-based materials [5]. Another option is to capture CO_2 by means of a post-combustion process, either for utilisation (BECCU), e.g., to produce e-fuels, or for permanent storage (BECCS), to generate negative emissions.

Several previous studies have examined the techno-economic performances of lignin extraction and carbon capture in pulp mills. For historical market conditions and steady-state operation, the techno-economic conditions for lignin extraction have been examined thoroughly by Olsson et al. [6], Tomani et al. [7], Benali et al. [8], and

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Culbertson [9]. Onarheim et al. [10,11] have studied the integration of BECCS into a softwood market pulp mill, and the economic potentials of BECCS and BECCU in various types of pulp and/or paper mills have been studied by Kuparinen et al. [12]. A comparison of the different carbon capture technologies has been carried out by Nilsson [13], and joint implementation of lignin extraction and carbon capture has been studied by Skoglund et al. [14].

This study adds to these previous works, by placing the pulp mill in the context of possible near-future markets for electricity, fuels and negative emissions. Thus, we compare investments in: (i) a condensing turbine for increased electricity generation; (ii) extraction of lignin for further refinement into fuels or chemicals; and (iii) carbon capture for either a BECCU or BECCS application. We examine how the economic viabilities of different technology options (or combinations thereof) depend on the price relations between feedstocks, products, and the potential value to be gained from negative emissions, and how the optimal dimensioning of mill processes is affected by highly variable future electricity prices. Furthermore, the carbon balance across the mill is analysed for different configurations to compare the mill's ability to contribute to fossil emissions reductions through the replacement of fossil fuels in hard-to-abate sectors or via negative emissions.

2. Method

This study compares investment options for an existing chemical pulp mill, towards increasing the value of side-streams from the mill production in future scenarios representing different market conditions. Fig. 1 provides an overview of the studied system, where the part representing the pulp mill is included in an optimisation model. The optimisation model minimizes investment and operational costs, where the conventional mill processes are assumed in-place and the options for investments include a condensing turbine for increased electricity generation, a lignin extraction plant, and a carbon capture system. All the combinations of these options are also considered. The optimisation model has been developed for previous work by the authors [15,16], but is in this study expanded with a carbon capture module and investment decisions. For a more comprehensive description of the optimisation model, see Appendix A: Pulp mill model.

The further refinement of lignin and CO_2 into end-products is not included in the optimisation model. However, it is considered in the studied scenarios, in order to provide well-grounded input data for the study, and it is handled in a post-analysis to provide a basis for discussions of the system implications and emissions-reduction potentials of the different choices of pulp mill. Lignin has a broad range of possible applications in fuels, materials and chemicals at varying levels of technological maturity [17]. In the studied scenarios, the lignin is assumed to be further refined into biofuels that can be used in the maritime sector. The captured CO_2 is assumed to be either combined with hydrogen into e-fuels, also for use in the maritime sector, or permanently stored to provide negative emissions. Maritime transport was chosen as an example application because of the large market size of transportation fuels, their role as a hard-to-abate sector in the decarbonisation of the economy, and the possibility for a direct comparison between a biorefinery and a Bio-CCU pathway. The scenario study and post-analysis is complemented with a sensitivity analysis of price tipping points in which key equations of the model is subjected to a wide range of potential market prices of lignin and CO_2 beyond the specific applications considered in the studied scenarios.

2.1. Scenarios

The model is subjected to a set of scenarios, representing developments that occur over time, from the present to Year 2040, with three different pathways for Year 2040. Each scenario is distinguished by assumptions regarding the market prices for lignin and CO_2 and the electricity price profiles.

To relate the prices of lignin and CO_2 to the considered applications for biofuels and e-fuels for the maritime transport sector, as well as for negative emissions, a set of assumptions has been drawn up. For the refining of lignin into biofuels, it is assumed that 1 MWh (103 l) of biodiesel can be produced from 3 MWh (0.4 t) of lignin, and that the cost of refining lignin into biodiesel is 25 €/MWh biodiesel [18]. For the production of e-fuels, a process is assumed in which hydrogen from the electrolysis of water is combined with CO_2 to generate e-methanol. It is assumed that 1 MWh of e-methanol can be made from 0.25 tonnes of captured CO_2, at a production cost of 113 €/MWh [19] (mainly the costs for electrolysers and electricity for hydrogen production). For negative emissions via BECCS, a cost for transport and storage of 100 €/t is used, which is within the range presented for the near-medium term by Oeuvray et al. [20], but notably higher than estimated in several other academic studies, such as that of Kjärstad et al. [21]. (Due to the large uncertainty and heavy dependence upon site-specific conditions, the higher estimate is chosen to avoid over-estimating the value of the BECCS option.)

The general assumptions and price data for the scenarios are:

- **Reference scenario:** Lignin is priced at 110 €/t, according to its use in the heat and power sector, and there is no market for CO_2.
- **Scenario 2030:** Biofuels can cover the demand for renewable maritime fuels. Based on an estimated market price for biodiesel of 100 €/MWh [22], lignin is priced at 175 €/t. There is still no market for CO_2.

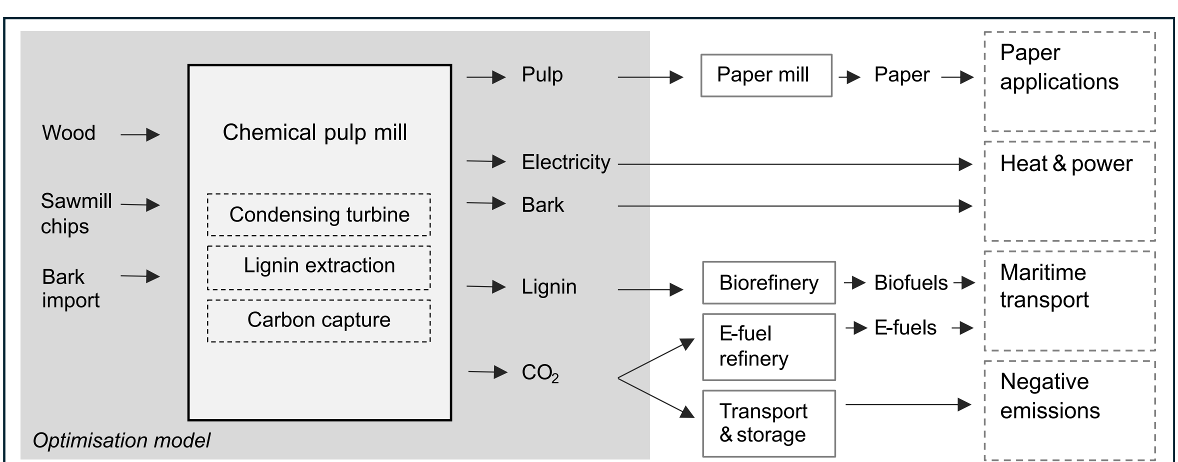

Fig. 1. Overview of the studied system. The shaded area shows the scope of the optimisation model.

- **Scenario 2040a:** The limited availability of biomass makes e-fuels a necessary complement for renewable maritime fuels. The market price for e-methanol, assumed at 125 €/MWh [23], sets the market price for both biofuels and e-fuels. This translates into a willingness-to-pay of 225 €/t for lignin and 50 €/t for CO_2.
- **Scenario 2040b:** The EU Emissions Trading System (EU ETS) has been adapted to allow for negative emissions credits to be sold at the same price as the cost for fossil emissions. Assuming an EU ETS credit price of 250 €/t (based on [24–26]) and subtracting the costs for transport and storage, the willingness-to-pay for captured CO_2 for negative emissions is assumed to 150 €/t, which is notably higher than the cost for e-fuels to the maritime sector. The market price for lignin is the same as in the 2040a scenario (225 €/t).
- **Scenario 2040c:** The input data are identical to the 2040b scenario, but all captured CO_2 is assumed to be used for e-fuel production.

Table 1 shows a summary of the assumed prices for lignin and CO_2 for the different scenarios. In all the scenarios, the wood price is 85 €/t (19 €/MWh) and the bark price is 70 €/t (16 €/MWh). For conversion between mass (dry weight) and energy, lower heating values of 4.5 €/MWh (16.2 MJ/kgds) for bark and wood and 6.9 €/t (24.8 €/kgds) for dried lignin were used.

For the electricity price profiles, projections made for Years 2030 and 2040 for south-central Sweden (price area SE3) are used. These have been obtained from a modelling study carried out by Öberg et al. [27] on the future electricity system, considering decarbonisation of the electricity sector together with new electricity demands from the industry and transport sectors. For the reference year, the historical prices for the same price area (SE3) for Year 2017 are used, which have an average value similar to those of the future projections, albeit smaller price variations. The electricity price profiles are shown in Fig. 2.

3. Results

Sections 3.1-3.2 and 3.4–3.5 cover the results from the optimisation model, i.e., within the system boundaries of the chemical pulp mill. Section 3.3, which addresses the system implications and emissions reduction potential, covers the extended scope, including the applications of lignin and CO_2 for fuels or as negative emissions.

3.1. Investment decisions and dispatch

Fig. 3 shows the investments in the condensing turbine, lignin separation plant, and CO_2 capture units and their utilisation in all the investigated scenarios, except scenario 2040c (for which the model results are identical to those for scenario 2040b). Table 2 lists the utilisation rates for the recovery boiler, bark boiler and back-pressure turbine, which were all assumed to be in place and not part of the model's investment decisions.

In the Reference scenario, the assumed values for lignin and CO_2 are relatively low relative to the electricity price. Thus, the mill only invests in a condensing turbine, which is dimensioned to maximise electricity generation from the mill. Both turbines are utilised at slightly below 100 % capacity because the flexibility inherent to the mill production processes allows the turbines to produce at above-average levels for some hours of high-price electricity, at the expense of lower production during low-price hours. The bark boiler is operated at its minimum level for nearly all hours of the year, as the assumed value of selling bark is higher than the value of the electricity generated from the bark, except for the hours with the highest electricity prices. Without a minimum load limit on the bark boiler, the bark boiler would have been out of operation during large parts of the year, maximising the export of bark instead.

In the 2030 scenario, with an assumed biofuel market with a higher lignin price (175 €/t compared to 110 €/t in the Reference scenario), the mill invests in both the condensing turbine and the lignin extraction plant. The lignin extraction plant is operated steadily (100 % utilisation) throughout the year but allows the recovery boiler to operate flexibly, as the boiler then becomes, in a sense, over-dimensioned and the black liquor storage tank serves as a buffer. This enables maximisation of the load of the recovery boiler during high-price electricity hours and reduction of the load during the rest of the year. The back-pressure turbine follows the pattern of operation of the recovery boiler, while the condensing turbine, which needs to recover its investment, operates throughout the year, except for the hours with the lowest electricity prices.

In the 2040a scenario, in which the demand for sustainable fuels is assumed to exceed the biofuel potential, thereby increasing the market prices for both lignin and CO_2, electricity generation is out-competed by the two other alternatives for most hours of the year. The net revenue (value minus costs) of producing lignin exceeds that of the captured CO_2, so the mill invests in lignin extraction up to the technical limit of how much can be extracted without losing the combustible properties of the black liquor. Only after this point is it beneficial to make investments in CO_2 capture corresponding to the remaining steam surplus. Since the lime kiln is the least-costly CO_2 stack, the capture investment is first focused on this unit, followed by the recovery boiler. The assumed conditions result in an installed capture capacity of 90 % of the emissions from the lime kiln and around 50 % of the emissions from the recovery boiler. For the approximately 6500 h with lower electricity prices, both boilers operate at their minimum loads and the condensing turbine is idle.

For the hours with the highest electricity prices (about 2000 h), the loads of the two boilers are increased, using stored black liquor and bark, enabling increased electricity generation from the back-pressure turbine and activation of the condensing turbine (which is assumed to be unrestricted in terms of the numbers of starts and stops). The carbon capture units can be operated at rated capacity throughout the full year, as the capture from the recovery boiler does not exceed the boiler's minimum load level, and the lime kiln is operating steadily.

In the 2040b scenario, in which CO_2 is assumed to be sold at 150 €/t for negative emissions credits, there is a notable gap between the willingness-to-pay for negative emissions and the cost to the mill of providing the capture, even after subtracting the costs for transport and storage. Therefore, the price for CO_2 is sufficiently high to out-compete lignin extraction, and the CO_2 capture from all stacks is maximised. The remaining surplus energy is used to produce electricity in the back-pressure turbine, with a utilisation factor that is similar to that of the reference scenario. The mill imports bark to maximise the use of the bark boiler during all hours of the year, by-passing the turbines when the electricity price is zero or negative, as the value of captured CO_2 exceeds the market price for bark.

The result indicating that the CO_2 capture process has 100 % utilisation in all cases where it is included shows that it is not relevant to over-dimension an investment in this technology to allow for flexible operation in response to electricity prices. This is due to the high capital costs in relation to the operational costs of the carbon capture technology. Therefore, no further examination was made of the impacts of MEA storage sizes, cycling times, etc.

Table 3 summarises the indicators of mill performance in the different scenarios, including the yearly production levels of pulp, lignin, CO_2 and electricity. In all the scenarios, the mill maximises the input of wood and the production of pulp according to the capacities of the processes in the fibre line.

Table 1
Summary of the assumed prices of lignin and CO_2 in the different scenarios.

Scenario	Reference	2030	2040a	2040b	2040c
Lignin [€/t]	110	175	225	225	225
Lignin [€/MWh]	16	24.50	31.50	31.50	31.50
CO_2 [€/t]	0	0	50	150	150

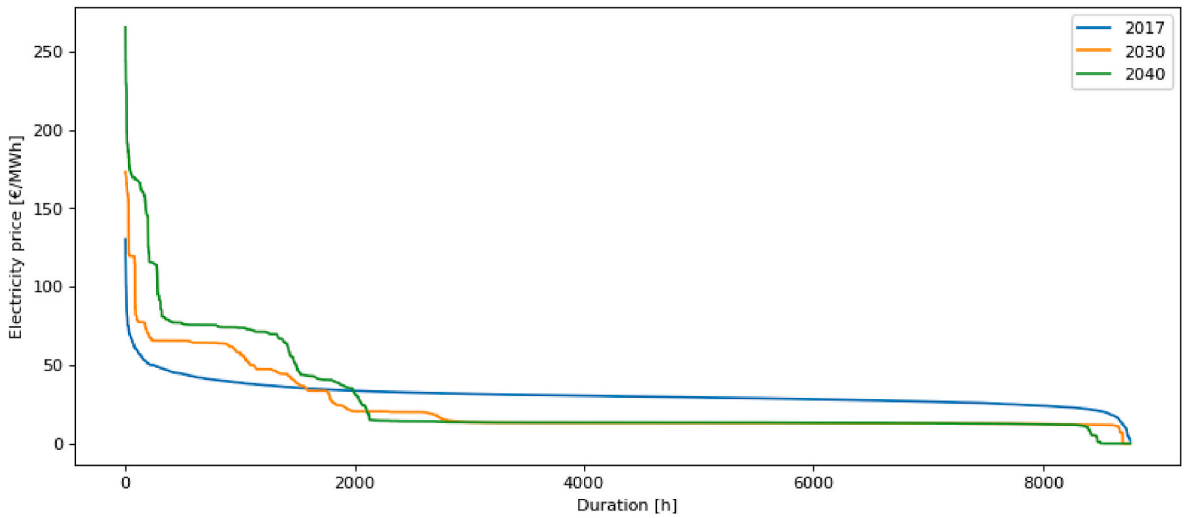

Fig. 2. Electricity price profiles used in the reference scenario (2017) and in the future scenarios representing Years 2030 and 2040.

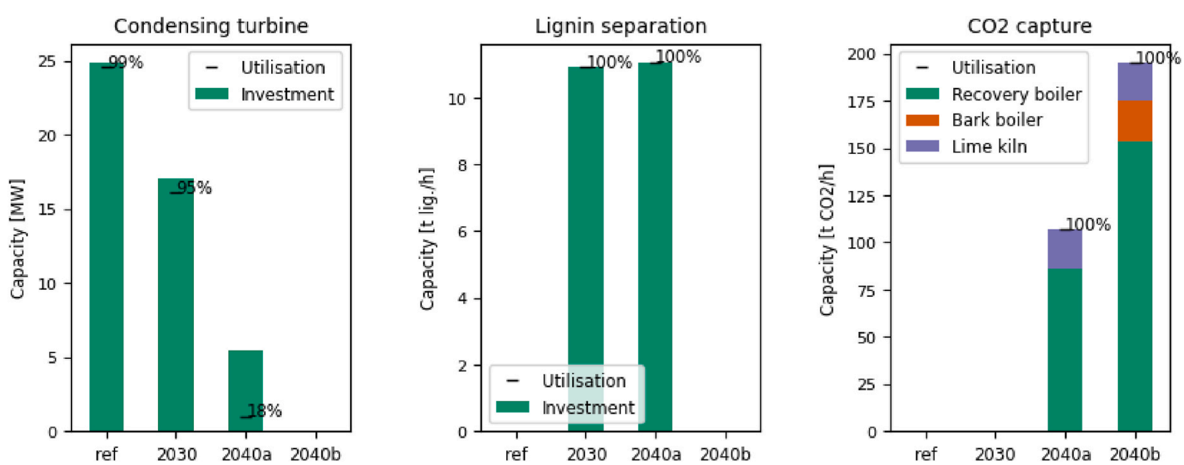

Fig. 3. Resulting investment and utilisation rates for the processes subjected to investment optimisation in the different scenarios.

Table 2
Utilisation of already installed processes in the reference and modelled scenario years.

	Reference	2030	2040a	2040b
Recovery Boiler	100 %	87 %	86 %	100 %
Bark Boiler	40 %	47 %	53 %	100 %
Back-pressure Turbine	94 %	80 %	78 %	96 %

Table 3
Summary of the indicators of mill performance in the different scenarios.

	Scenario			
	Reference	2030	2040a	2040b
Wood input [kt]	1640	1640	1640	1640
Pulp production [kt]	777	777	777	777
Lignin production [kt]	0	96	97	0
CO_2 captured [kt]	0	0	935	1711
CO_2 released [kt]	1779	1593	666	190
CO_2 captured [share]	0 %	0 %	58 %	90 %
Bark net export [kt]	32	25	18	−34
Electricity production [GWh]	1180	966	813	990
- Back-pressure turbine [GWh]	971	829	805	990
- Condensing turbine [GWh]	209	137	9	0
Electricity use [GWh]	538	538	651	744

3.2. *Carbon allocation and electricity trade*

Fig. 4 shows Sankey diagrams of the biogenic carbon flows through the mill and the associated carbon efficiencies (the shares of input carbon atoms that leave the mill in products or as captured CO_2) and net electricity generation levels, for all scenarios except scenario 2040c (for which the model results are identical to those for scenario 2040b). Since only around 40 % of the input carbon ends up in the pulp, more than half of the biogenic carbon atoms are used for the generation of industrial steam and electricity and thereafter released to the atmosphere as CO_2, in the reference case. It should be noted that in real mills, a small fraction (a few percentage points) of the carbon is typically retrieved as by-products that are not included in the model, such as tall oil, turpentine, etc.

In scenario 2030, the share of carbon that leaves the mill in products is increased through the extraction of lignin. However, the impact of lignin extraction on the carbon efficiency is small at the levels studied (around 25 % of the lignin). Even with a theoretical lignin extraction level of 100 %, the carbon efficiency could not exceed 70 % from this measure alone. With 90 % of the CO_2 captured in the 2040b scenario, a total carbon efficiency of 94 % is reached.

The increased carbon efficiency in the future scenarios comes with a penalty for the energy balance, which severely reduces the mill's ability to deliver surplus electricity. With 7 % of the carbon extracted as lignin, 33 % of the surplus electricity is lost, and when lignin extraction is

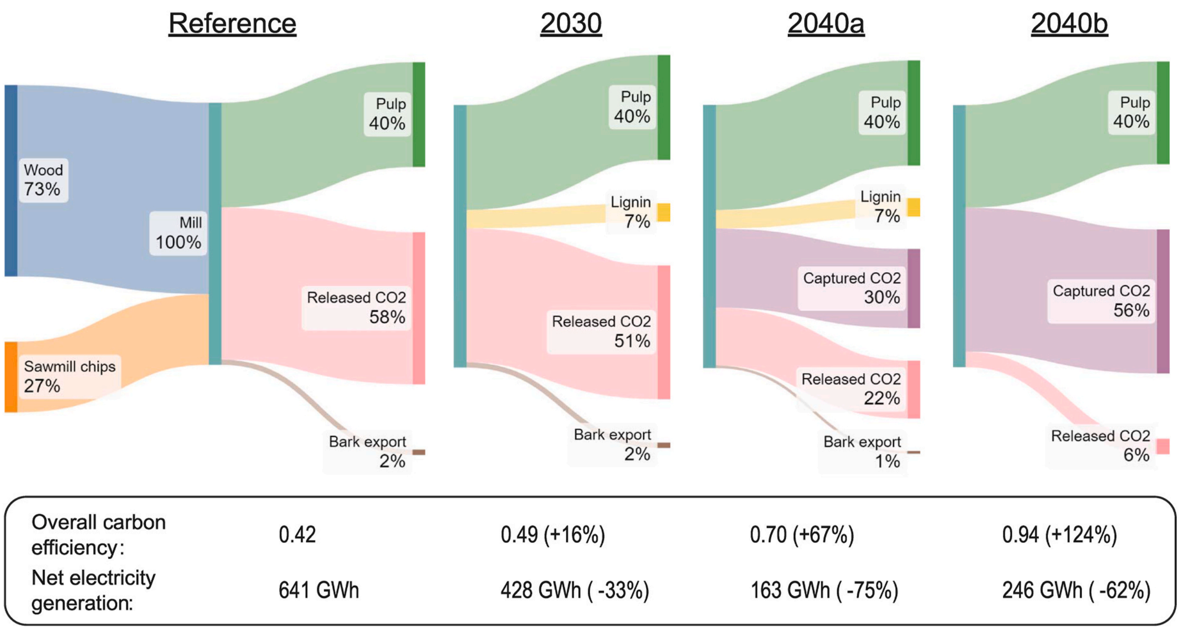

Fig. 4. Biogenic carbon flows through the mill and associated carbon efficiencies and net electricity generation levels, for the different scenarios. The percentages in parentheses indicate the differences compared to the Reference scenario.

combined with carbon capture most of the surplus is eliminated. However, as shown in our previous work [16], lignin extraction does not necessarily reduce the level of electricity generation if there is capacity available in the fibre line to increase the overall wood throughput when lignin is removed from the black liquor.

In the 2040b scenario, even though the same low level of carbon as in the reference scenario leaves the mill in products, 90 % of the carbon that is used for energy generation is captured, transported and can be stored as negative emissions. The energy consumption of the capture process drastically reduces the electricity generation potential, albeit to a lesser extent than in the scenarios with lignin extraction, as each carbon atom in the black liquor generates more energy when combusted than it requires for its capture. However, when lignin extraction is combined with flexible recovery boiler operation, as in the 2040a scenario, the loss of electricity production can be focused to less-valuable hours, reducing the economic impact. For that reason, the net value of the traded electricity is almost equal (7.7 M€ vs. 7.9 M€) in the 2040a and 2040b scenarios, despite the fact that 50 % more electricity is exported in the 2040b scenario.

3.3. System implications and emission-reduction potential

To assess the wider consequences of the mill's investments and operation, Table 4 presents how much fuel could be manufactured from the extracted lignin or captured carbon, e.g., to replace fossil fuel in the maritime sector. The table also shows the amounts of fossil CO_2 emissions that would be avoided in the consumption stage when the fossil fuel is substituted, or (for scenario 2040b) the levels of emissions that could be offset from the negative emissions. The fifth scenario, 2040c, is included, where the mill is assumed to operate in a manner identical to scenario 2040b, maximising CO_2 capture, but using all the CO_2 for e-fuel synthesis.

The potential associated with replacing fuels and reducing emissions is higher with CCU than with lignin-based biofuels, considering only the availability of carbon atoms. This is because the energy in the biofuel originates from the lignin itself, and the assumed refinery process requires 3 MWh of lignin to produce 1 MWh of fuel. In contrast, with the electro-fuel option, the carbon is only used as a chemical component in the fuel, while the majority of the energy comes from the hydrogen part of the fuel (in the form of electricity if hydrogen is generated via electrolysis).

The most fuel by far is produced in the 2040c scenario, when there is no lignin extraction and 90 % of the CO_2 is captured for utilisation. The synthesis of e-fuels, however, requires electricity on the TWh scale, which is indicated in the table as *External electricity use*. From the 1.9 $MtCO_2$ captured from the model mill, around 6.85 TWh of e-fuel could be synthesised, which would require around 11 TWh of electricity for the electrolysis process [23]. While thorough life-cycle assessments of the climate effects of a CCU case (such as scenario 2040a) and a CCS case (such as scenario 2040b) are beyond the scope of this study, it is noteworthy that the net emissions avoided by replacing 6.8 TWh of fossil methanol with the equivalent amount of bio-based e-fuels (1.9 $MtCO_2$) are equivalent to what could have been compensated through sequestration and storage of the same CO_2.

Table 4
Comparison of system-related indicators for the future scenarios.

	2030	2040a	2040b	2040c
Biofuel produced (GWh)	226	229	0	0
E-fuel produced (GWh)	0	3740	0	6850
Internal electricity use (GWh)	172	427	462	462
External electricity use (GWh)	0	6140	0	11,220
Fossil CO_2 emissions avoided (kt)	57	993	1711	1711
Electricity use per fuel created (GWh/GWh)	0.76	1.65	0	1.71
Electricity use per avoided fossil CO_2 emissions (GWh/kt)	3.04	6.61	0.27	6.83

3.4. Price tipping points and sensitivity to investment costs

Fig. 5 presents the results of a sensitivity analysis showing the product price levels at which that the different technologies are competitive, based on the mass and energy balances of the model mill. The three panels (a, b, c) show the equilibrium market prices for which the net revenues from producing two alternative products are equal, considering both the investment and operational costs. For example, for CO_2 vs. electricity (panel a), if the electricity price is at the Year 2019 average of 40 €/MWh, the market price for CO_2 must be higher than 55 €/t for the mill to choose investment in carbon capture over investment

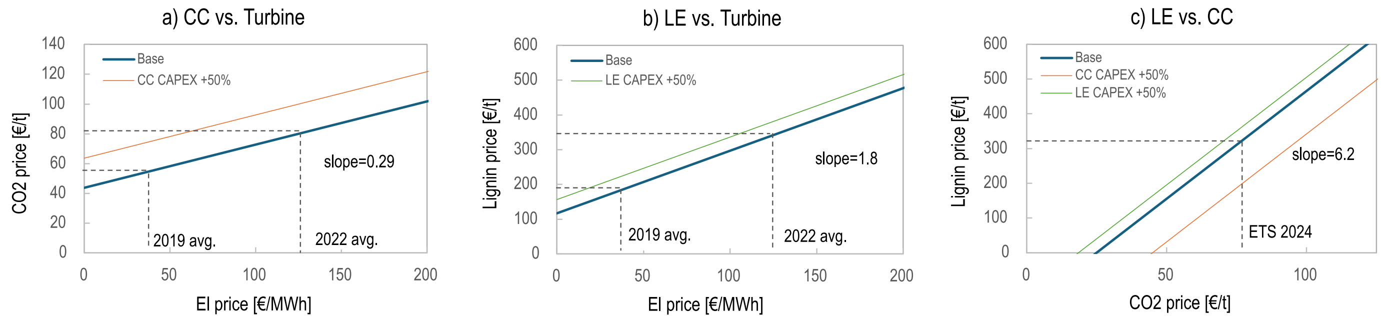

Fig. 5. Tipping points for investment decisions in a carbon capture system (CC), a lignin extraction system (LE) or a condensing turbine, for different price combinations of electricity, lignin and CO_2. The average electricity prices for the SE3 region for Year 2019 (typical historical prices) and Year 2022 (unusually high prices), and the Year 2024 EU ETS price for CO_2 emissions are shown for reference. The orange and green lines show the impact of higher investment costs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

in a condensing turbine.

Panel a in Fig. 5 shows the equilibrium line for investments in carbon capture or in a condensing turbine. The graph underlines the importance of the electricity price in determining the steam cost for CO_2 capture, which has a strong impact on the specific capture cost. For each tonne of CO_2 captured, 1.4 tonnes of low-pressure steam (1.1 MWh) are required, which could otherwise have been used to produce 0.17 MWh of electricity in the condensing turbine. With the electricity prices used in the scenarios, this implies steam costs in the range of 0–22 €/t (average, 5.3 €/t) with the electricity prices of the reference year, and 0–45 €/t (average, 4.6 €/t) for the electricity prices of Year 2040. These values can be compared with the more general assessment of steam prices in the literature, reporting between 2 €/t for steam from recovered waste heat and 25 €/t for steam from a natural gas-fired boiler [28]. In addition, the CO_2 liquefaction process requires 0.12 MWh of electricity per tCO_2. When the alternative costs for electricity generation are included, the specific cost of carbon capture thus varies between the hours of the year. Assuming that the energy cost for carbon capture (in €/tCO_2) is 0.29 (i.e., 0.17 + 0.12)-times the electricity price (in €/MWh) and the assumed capital costs (31.2 €/t), fixed O&M (8.7 €/t) and non-energy variable O&M (5.6 €/t) are added, the specific cost for carbon capture from the recovery boiler is in the range of 46–68 €/tCO_2 for the electricity prices of the reference year and 46–91 €/tCO_2 for the electricity prices of Year 2040.

Panel b in Fig. 5 shows the equilibrium line for investments in lignin extraction or a condensing turbine. This relationship was thoroughly analysed in our previous study, leading to the conclusion that for lignin extraction to be more valuable than the corresponding electricity generation, the lignin price (€/t) must be 1.8-times the electricity price (€/MWh), in addition to the non-energy operational costs of lignin extraction (assumed to be 40 €/t) and the capital costs [29]. The lignin price range examined in the optimisation scenarios (110 €/t for heat and power applications and 175–225 €/t for biofuel applications) can be compared with values reported in the literature for applications in green chemicals that potentially may be higher. Robinson et al. [30] have evaluated different production paths to supply aromatic monomers, phenols-formaldehyde resin, and aromatic aldehydes/acids and found a selling price for kraft lignin between 150 and 350 €/t depending on market conditions and policy.

Panel c in Fig. 5 indicates the relationships between the prices of lignin and those of CO_2, via their respective relationships to the electricity price presented in the two preceding panels. This validates the results from the scenario analysis, that if CO_2 is sold at its production cost (around 50 €/t) the corresponding lignin price (150 €/t) is well within the price range for lignin applications. If, however, CO_2 is priced in line with the EU ETS, the CO_2 prices at the ETS price for Year 2024 [31] would match lignin prices above 300 €/t, which is already close to the maximum market value of kraft lignin (350 €/t), as reported by Robinson et al. [30], and with CO_2 prices of 100 €/t, the lignin prices must significantly exceed this level for lignin extraction to become competitive.

A sensitivity analysis was also carried out to study how the equilibrium lines change with different assumptions for the investment costs. The orange and green lines in Fig. 5 show how the equilibrium line is shifted in parallel to the axes for a 50 % increase of capital expenditures for one technology at the time. With carbon capture being a capital-intensive technology, such a difference in investment cost assumptions considerably affects the tipping points and would shift the balance in favour of lignin extraction for some realistic combinations of lignin and CO_2 prices. This may be especially relevant for early ("First-of-a-kind") projects that may likely be more-expensive than the literature suggests.

3.5. *Value of flexible operation*

The comparison described above (as in many previous studies) is based on a static representation of prices, with annual averages used for electricity prices. However, the price of electricity, and thus the operating strategy, is set on an hourly basis, while the cost/value of fuels and products exhibits a slower price evolution. Therefore, in addition to the direct comparisons shown in Fig. 5, we also identified the price combinations for which it is viable to invest in multiple technologies for part-time utilisation so as to benefit from variable electricity prices, i.e., how the combined revenues of two technologies minus their investment costs compare with separate investments in either of the two technologies, when the full electricity price profile is considered.

Neither the electricity prices of the reference year nor those projected for Year 2030 motivate investments in several technologies. For the more-variable electricity prices of Year 2040, a lignin price in the range of 150–200 €/t (i.e., slightly lower than what was assumed in the Year 2040 scenarios) would motivate dimensioning of the condensing turbine for part-time utilisation. The reasons why there are still investments in multiple technologies in the model results from the 2030 and 2040a scenarios are: 1) that lignin extraction is limited not only by the availability of steam, but also by a set technical limit on maximum extraction; and 2) that, in scenario 2040a, the combination of condensing turbine and carbon capture is favoured by flexible boiler operation, which is made available in the bark boiler when less bark is exported and in the recovery boiler when lignin is extracted.

Additional investment calculations were performed with the historical electricity prices of Year 2022 for the SE3 region, which are even more-variable than the Year 2040 projections (ranging from −2 €/MWh to 800 €/MWh, with an average of 119 €/MWh). For the electricity price profile of Year 2022, investments in both a condensing turbine and lignin extraction with part-time utilisation is motivated for all lignin prices in the range of 250–600 €/t, and a combined investment in a condensing turbine and carbon capture would be motivated for all CO_2 prices in the range of 75–120 €/t.

Another incentive for investment in both carbon capture and lignin extraction, which was not covered by the model, is that the CO_2 that is used in the lignin extraction process could be supplied internally. However, the magnitude of the CO_2 demand for lignin extraction is small, and the economic gains from this synergy would be minor.

4. Discussion

4.1. Technology options

The studied scenarios and the complementary sensitivity analysis of price tipping points jointly provide insights on the implications for the pulping industry of possible future market and policy development. The studied technology options represent a diverse portfolio of technologies, including one power-generation technology (the condensing turbine), one bio-chemical technology (Lignin extraction) and one carbon capture technology (chemical absorption with MEA). These technologies were selected because of their technical maturity and established positions as benchmark processes in the scientific literature. Future work could expand the analysis to include technologies at a lower technology readiness level and compare the options covered in this study also with a thermo-chemical technology option such as gasification [32] or hydrothermal liquefaction [33] of black liquor.

4.2. The value of electricity versus the value of green carbon atoms

The results for the future scenarios describe a shift in the role of the pulp mill over time. In the reference and 2030 scenarios, the mill acts as a net electricity producer and flexibility provider, supporting the transition of the electricity sector (and, indirectly, the electrification of the heating, transportation and industry sectors) during this period. In the Year 2040 scenarios, where the energy transition has reached the hard-to-abate sectors, it is more profitable for the mill to supply green carbon atoms than to supply electricity. However, to enable these diverse roles, different investments are required for the different eras, i.e., investments in condensing turbines in the near future and in BECCS/CCU/lignin extraction in the longer run, which can be difficult to achieve if invested assets should have the time to recover costs. Therefore, it is important for decision-makers not only to consider the optimal choice for a selected target year, but also the transition pathway.

This shift in drivers is clear for the 2040a scenario, when the turbines operate at the minimal level for most hours of the year, using all the available energy for lignin extraction and carbon capture during this time. If the projected electricity prices for Year 2040 and beyond are realised, and the value of the green carbon is clearly higher than the value of generated electricity (for most hours of the year), several more-radical changes to the mill could become relevant but these were not available to the model mill within the present study. A few first steps could be to remove the lower operational limit on the back-pressure turbine (or exclude the turbine completely) and add an electric boiler or heat pump for steam supply, allowing for maximal lignin extraction together with full carbon capture from all the stacks. It should be noted that the tipping points between CO2 price and electricity price would differ if the steam is sourced through these alternative means, compared to those presented in section 3.4, where abundant low-pressure steam was assumed to be available.

Although the quantitative results presented in this work apply specifically to the model mill, the general trends discussed in this section should apply also to chemical pulp mills with other specifications. For the case of integrated pulp and paper mills, adding carbon capture or lignin extraction technologies would not only reduce the electricity export but also require additional energy input, since those are typically net consumers of electricity. The additional energy could for example be supplied through an additional biomass boiler (with externally sourced biomass) or high-temperature heat pumps.

4.3. Demand for and potential supply of renewable transport fuels

To relate the modelled scenarios to the Swedish energy market, the potential supply levels of lignin-derived biofuels and e-fuels from the CO_2 captured from the model mill are scaled to Sweden's 20 largest pulp and paper mills (20,000 kt/year of CO_2 i.e., 10-times that of the model mill [34]) and compared with the requirements for maritime fuels imposed by the FuelEU Maritime regulation. FuelEU Maritime mandates that the greenhouse gas intensity of the energy used on ships be reduced by 2 % from Year 2025, increasing to 80 % by Year 2050, relative to the Year 2020 average level [35]. (The emissions reduction quotas of the regulation are translated to demands for renewable fuels and applied to the maritime sector in Sweden, assuming that the overall energy demand for this sector remains at current levels, i.e., 28 TWh, derived from Ref. [36].) The comparison, illustrated in Fig. 6, shows that lignin-based biofuels (2.3 TWh) could theoretically supply the demand for sustainable maritime fuels for Year 2030, as assumed in the formulation of the scenarios, but only a minor fraction of the demand for Year 2050. On the contrary, the potential for e-fuel production from pulp mill CO_2 (68 TWh) greatly exceeds the demand from the Swedish maritime sector. Although there undoubtedly exist sources of bio-fuels other than kraft lignin and there are demands other than for maritime fuels, the data support the idea that there is a point in time between Year 2030 and Year 2050 when sustainably sourced biofuels will become insufficient to meet the demand of the transport sector and e-fuels will become a necessity.

The comparison above considers only the carbon component of electro-fuels, ignoring the hydrogen component. In the near future, CCU may be limited more by access to low-priced electricity for hydrogen production than by access to CO_2, and therefore, the choice between utilisation or storage of captured carbon also heavily depends on the development of the electricity sector.

In the European context, there is greater demand for maritime fuels (500 TWh/year for all naval trips to/from EEA ports, derived from Ref. [37]) and relatively lower levels of available biogenic CO_2 (150–250 $MtCO_2$ [38], corresponding to 600–1000 TWh). This means that meeting the entire current demand from the maritime sector with e-fuels derived from captured biogenic CO_2 could require the capture of almost all biogenic CO_2 emissions in Europe. Nevertheless, the Year 2040 quota of 31 % should be well within reach, from a purely CO_2 availability perspective.

In addition to the FuelEU initiative, the demand for sustainable maritime fuel is affected by the development of the EU ETS-1, where the maritime sector is gradually included from Year 2024 and fully phased in by Year 2026 [39]. Fig. 7 shows the assumptions made regarding supply costs for the different fuel options stated above, with a range of ETS allowance prices added to the fossil option. According to recent

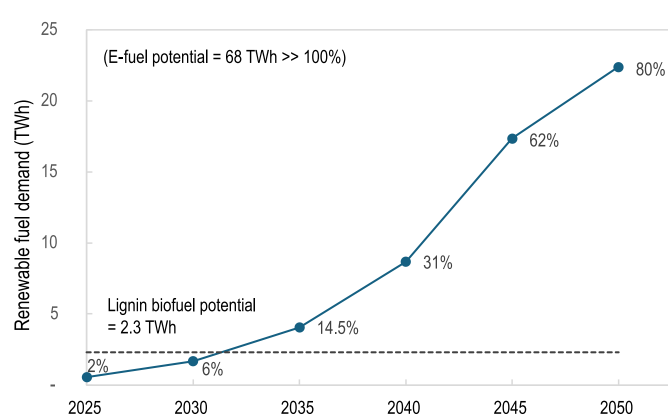

Fig. 6. Renewable fuel demands for the maritime sector in Sweden, based on the emissions reduction quotas set by the FuelEU regulation, scaled to the current Swedish demand for maritime fuels. Estimated potentials for lignin biofuels and bio-based e-fuels are shown for comparison.

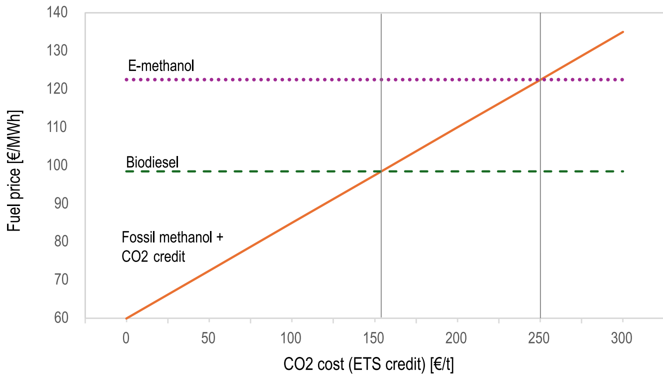

Fig. 7. Assumed supply costs for fossil methanol, biodiesel and e-methanol, where the supply cost for fossil methanol increases with the EU ETS credit price.

projections for the development of the ETS price, prices of 150 €/t are likely to occur around Year 2030 [24] and prices well above 250 €/t are expected by Year 2040 [25] or shortly thereafter [26]. This suggests a timeline for when biofuels and e-fuels become competitive that is similar to the reasoning based on the FuelEU regulation.

However, the emissions allowance cap of the EU ETS-1 beyond Year 2030 is not yet decided. If the EU decides to keep the current linear reduction pace (2.2 % per year [39]) also beyond Year 2030, the cap will reach zero in Year 2039, making the emissions reduction quotas redundant because the ETS policy imposes a tighter limit than the sector-specific emissions reduction quotas. In such a case, the scenarios for Year 2040 studied in the present work will be relevant already during the 2030's.

4.4. Implications for policies aiming for negative emissions

Based on the results presented in Section 3.3, it could be argued that capturing CO_2 and storing it, as in scenario 2040b, is the option in which the pulp mill can contribute the most to meeting the CO_2 targets, as this delivers a net emissions reduction, which out-competes scenario 2040a and is on par with scenario 2040c, while also delivering electricity that can be used to decarbonise other sectors.

A problem that would emerge if the maritime sector, and other sectors with similar abatement costs, decide to adopt a strategy of compensating fossil emissions with negative emissions from BECCS, is that the potential for BECCS is limited. As argued previously [40], using BECCS to compensate for emissions that could have been mitigated through other measures risks undermining the possibility of compensating for residual emissions in even-harder-to-abate sectors, and would eventually prevent using BECCS to achieve overall net-negative emissions.

Because of the limited potential, the market price for captured CO_2 would likely rise to several hundred €/t if the negative emissions credits for BECCS are counted on a one-to-one basis as emissions avoidance and the ETS cap approaches zero. Such strong economic incentives for BECCS would likely lead to increased prices for biomass resources. Hu et al. [41] have studied the forest sector in the Nordic region in a scenario with a CO_2 price of 300 €/t, finding that market prices for pulpwood and residues increase, which in turn leads to increased harvest and/or import of wood. If the increased harvest (locally or at the source of import) leads to a depletion of the carbon stock in the forest, they argue, there is a risk of "carbon sequestration leakage", which would counteract the purpose of a BECCS policy.

5. Conclusion

In the study presented in this paper, an optimisation model representing a chemical pulp mill is used to investigate potential investments in technologies for additional electricity generation, lignin extraction and carbon capture under various scenarios where, over time, the values of the biogenic by-products of the mill increase compared with the reference scenario, while the electricity prices become more variable.

In the reference scenario, which represents the present market conditions, the model mill invests in a condensing turbine for increased electricity generation. In a scenario that should reflect Year 2030, the mill invests in both a lignin extraction plant and a condensing turbine. For the scenarios that should reflect Year 2040, new demands from hard-to-abate sectors and/or a policy regarding negative emissions drive the mill to prioritise increased carbon efficiency over electricity generation, shifting investments away from the condensing turbine to lignin extraction and carbon capture. In the scenario in which both lignin and CO_2 are priced based on the demand for sustainable fuels, lignin extraction is favoured over carbon capture, although the technical limitations of lignin extraction motivate a combination of both technologies. When instead the CO_2 is valued by the demand for negative emissions, according to the price of emissions allowances in the EU ETS, lignin extraction cannot compete with carbon capture.

The share of green carbon atoms used for products can be improved with lignin extraction, albeit only to a certain level. For greater improvements, and for the highest potential to reduce fossil emissions in other sectors, carbon capture is required. Carbon capture with storage has an advantage over utilisation when both the CO_2 and electricity balances are considered, although promoting storage over utilisation may hinder decarbonisation of the economy as a whole.

CRediT authorship contribution statement

Simon Ingvarsson: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Mikael Odenberger:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Filip Johnsson:** Writing – review & editing, Supervision, Conceptualization.

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Appendix A. Pulp mill model

The reference chemical pulp mill used in this work is illustrated in Figure A1. It is a stand-alone mill with an annual capacity of 730,000 air-dry tonnes (ADT) of bleached softwood pulp. The model is based on the steady-state description in Åforsk Model Mills 2010 [4], which represented the best-available technology at the time of its publication.

Conversion from biomass to steam takes place in a recovery boiler, which combusts the black liquor, and in a separate bark boiler. Electricity is produced by two generators, one of which is connected to a back-pressure turbine and the other to a condensing turbine. The generated electricity and steam are supplied to industrial processes throughout the mill, which means that the mill is self-sufficient in terms of heat and is a net exporter of electricity. The lime kiln is fuelled with gasified bark, such that no externally supplied fuels are needed.

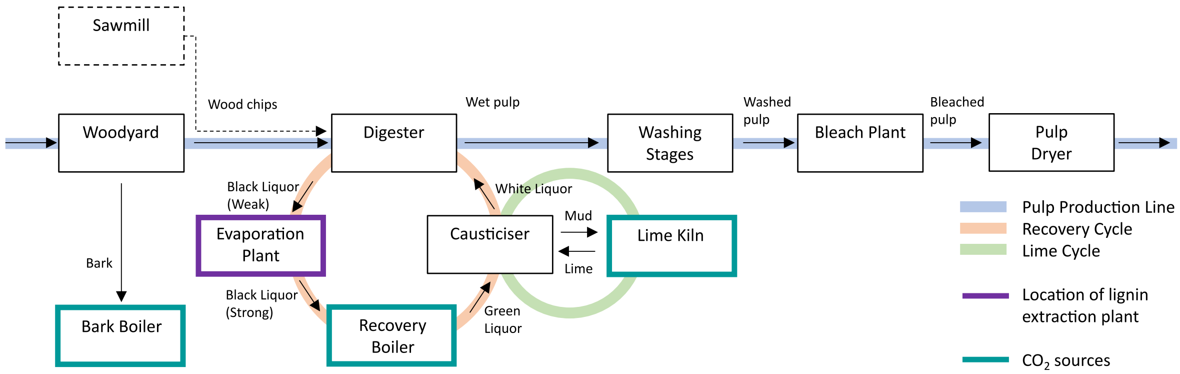

Fig. A1. Overview of the model pulp mill.

The mathematical representation of the model mill is presented in detail in our previous paper [15]. It is a linear programming (LP) model that gives the optimal material, steam, and electricity flows throughout the mill with hourly time resolution, to maximise the profits of the mill, given the prices of all the input and output commodities. In the present work, the model has been expanded with investment decisions, such that the condensing turbine, lignin extraction plant and carbon capture units are dimensioned endogenously within the model.

Equation (A1) gives the objective function, where TC is the total cost of the mill, I_p is the invested-in capacity of the process p, $E^{use}_{p,t}$ is the electricity consumed in each process p, $E^{gen}_{\theta,t}$ is the electricity generated in each turbine θ, $M^{ext}_{p,t}$ are the external supplies fed to any process, $M^{out}_{p,t}$ are the product outputs of dry pulp, lignin, CO_2 and bark, and c_x are the prices associated with each variable I, E or M.

$$\min TC = \sum_{P_{inv}} c^{inv}_p I_p + \sum_T \left[c^{el}_t \left(\sum_P E^{use}_{p,t} + \sum_\Theta E^{gen}_{\theta,t} \right) + \sum_P c^{ext}_p M^{ext}_{p,t} - \sum_{P_{out}} c^{out}_p M^{out}_{p,t} \right] \tag{A1}$$

In our previous work [29], additions were made to the model, so as to represent a lignin extraction process similar to LignoBoost [5] that is installed as an extra intermediate step within the evaporation plant (purple box in Fig. A1). Fig. A2 shows a schematic of the evaporation plant and recovery boiler, including the lignin extraction process.

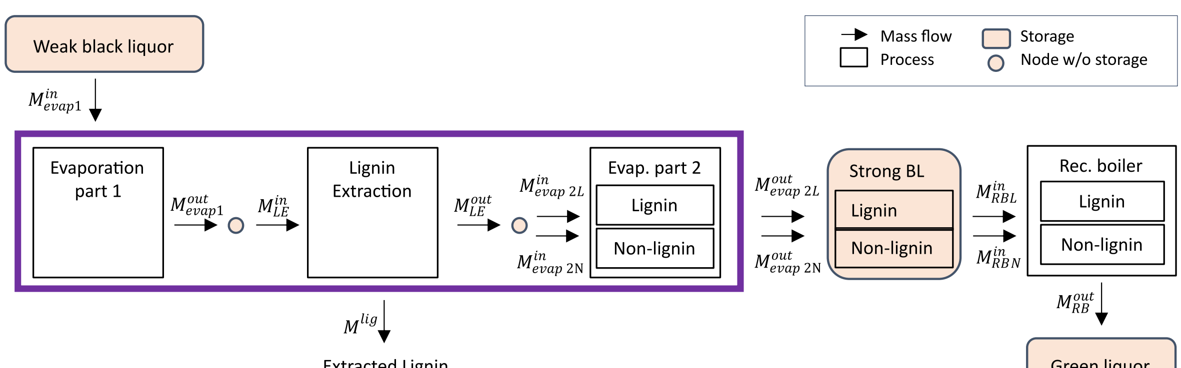

Fig. A2. Schematic of the evaporation plant and recovery boiler, including the lignin extraction process.

In the present work, the model mill is further extended with a carbon capture module that is connected to the three flue gas stacks: the recovery boiler (RB), the bark boiler (BB), and the lime kiln (LK). A schematic of the carbon capture module is presented in Fig. A3 and a summary of the model nomenclature is given in Table A1. The module represents a conventional post-combustion, amine-based system with separate absorbers for each flue gas stack, but with a joint stripper and liquefaction unit. A study of the potential implementation of carbon capture at a Swedish pulp mill [42] has shown that with several stacks, a joint stripper and liquefaction unit is cost-optimal, while there are minor differences between having a large central absorber unit or one small absorber per stack. Similar conclusions have been reached for carbon capture in other sectors [43,44]. In the model, the invested capacity I_p of each absorber, as well as the stripper and liquefaction units are dimensioned separately.

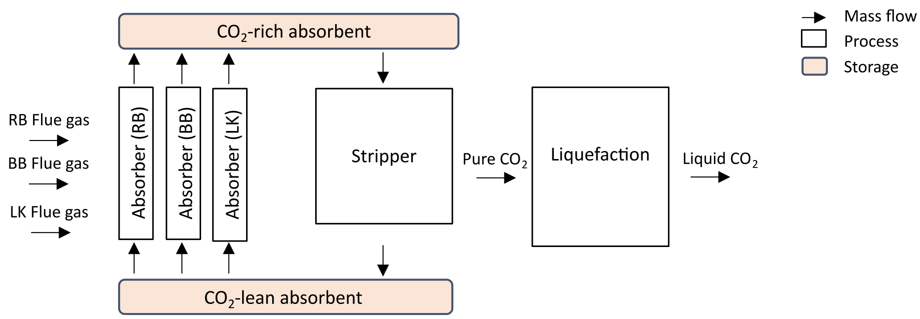

Fig. A3. Schematic of the carbon capture module of the model mill.

Table A1
Model nomenclature

INDICES		
Symbol	Unit	Definition
t	–	time-steps
p	–	mill processes, including boilers and kilns
Θ	–	turbines
EXOGENOUS VARIABLES		
Symbol	Unit	Definition
c^{el}_t	€/MWh	Electricity price at time step t
c^{ext}_p	€/t	Cost for external supply to process p
c^{inv}_p	€/(t/h)	Investment cost for process p
c^{out}_p	€/t	Selling price for output from process p
f_{lm}	t/t	Loading mass factor (absorbent to CO_2 ratio)
r	t/t	CO_2 to fuel ratio
TC	€	Total cost
$C^{abs}_{t,p}$	t	Hourly flow of CO_2 to the absorber associated with process p
C^{liq}_t	t	Hourly flow of CO_2 to the liquefaction unit
$E^{gen}_{\theta,t}$	MWh	Hourly electricity generation in each turbine θ
$E^{use}_{p,t}$	MWh	Hourly electricity consumption in each process p
I_p	t/h	Invested-in capacity of each process p
$M^{ext}_{p,t}$	t	Hourly external supply to process p
$M^{in}_{p,t}$	t	Hourly material/absorbent input to process p
$M^{out}_{p,t}$	t	Hourly material/absorbent output from process p
$M^{s}_{p,t}$	t	Hourly storage level upstream to process p

The CO_2 flow entering each absorber, $C^{abs}_{t,p}$, is restricted by the fuel input of the associated boiler or kiln p at each time-step t according to Equation (A2), where r is the ratio between the fuel input and CO_2 output.

$$C^{abs}_{t,p} \leq r \times M_{t,p} \tag{A2}$$

For each absorber (associated with process p), the amine flow, $M^{in,abs}_{t,p}$, is proportional to the flow of CO_2 entering the absorber at each time-step t, $C^{abs}_{t,p}$, according to Equation (A3), where f_{lm} is the specified loading mass factor for the solvent medium.

$$M^{in,abs}_{t,p} \leq f_{lm} \times C^{abs}_{t,p} \tag{A3}$$

The circulation of the solvent medium between the absorber and stripper is modelled as shown in Equations (A4) and (A5), where M^s_t are storage levels, M^{in}_t and M^{out}_t are process inputs and outputs, and M^{ext}_t are external supplies. The operation of the absorbers and the stripper is also restricted by the maximum and minimum operational limits (the model does not allow for a complete turn-off of any process).

$$M^{s,abs}_t \leq M^{s,abs}_{t-1} + M^{out,str}_t - \sum\nolimits_{abs} M^{in,abs}_{t,p} + M^{ext,abs}_{t,p} \quad \forall t \in T \tag{A4}$$

$$M^{s,str}_t \leq M^{s,str}_{t-1} + \sum\nolimits_{abs} M^{in,abs}_{t,p} - M^{out,str}_t + M^{ext,str}_t \quad \forall t \in T \tag{A5}$$

The amount of CO_2 that enters the liquefaction unit at each time-step, C^{liq}_t, is restricted by the stripper output, $M^{out,str}_t$, according to Equation (A6).

$$C^{liq}_t \leq \frac{1}{f_{lm}} M^{out,str}_t \tag{A6}$$

Data and assumptions.

The process capacities, through-put times and capacities of the intermediate storage units of the conventional mill processes, boilers, and the back-pressure turbine are given exogenously to the model. For further details, see our previous publication [15].

The capacities of the condensing turbine, lignin extraction plant, CO_2 absorbers, CO_2 stripper, and CO_2 liquefaction are decided endogenously within the model. The investment cost assumptions for these units are presented in Table A2, where the total capital cost has been annualised based on the interest rate and an economic life-time. The assumptions made for the carbon capture units are based on the work of Onarheim et al. [11], whereas the total investment cost for the carbon capture plant is assumed to be split into one-third for the absorber and two-thirds for the stripper (for a more-detailed cost breakdown, see Biermann et al. [28]).

In reality, the investment costs depend strongly on the scale, while the model shows a linear relationship between unit size and investment cost. To ensure that minor investments in BECCS are directed to the lime kiln, the flue gases of which have the highest CO_2 concentration, the investment cost for the recovery boiler absorber was set slightly higher than that for the lime kiln absorber (despite the fact that a full-sized investment in the recovery boiler would be less expensive per unit capacity according to the reference). For a discussion on the investment costs for the lignin extraction plant, the reader is directed to our previous paper [29].

Table A2
Cost assumptions for investments.

Process	Capital requirement (€/t/h CO_2 capacity) (k€/t/h lignin capacity) (k€/MW turbine capacity)	Annualised investment cost (7.5 % interest rate, 20-year life-time) (k€)
Absorber recovery boiler	930	91
Absorber bark boiler	1050	103
Absorber lime kiln	920	90
Stripper (joint)	1940	190
CO_2 Liquefaction	80	8
Lignin extraction	7000	690
Condensing turbine	1000	98

The technical parameters for the lignin extraction module were the same as in our previous work [29], and the minimum lignin content of the black liquor was set to correspond to 30 % lignin extraction. The technical parameters for the carbon capture were set according to Table A3. The loading mass factor is derived from a previous study [10], which describes a carbon capture process that uses monoethanolamine (MEA) as the solvent. The solvent could be replaced by a more-efficient alternative, such as AMP-PZ, which might reduce the operation and maintenance costs. Nonetheless, the MEA process was chosen because of its established position in the literature.

Finally, one definition and a few assumptions were made for the post-analysis. Carbon efficiency is defined as the share of input carbon atoms that leaves the mill in products or as captured CO_2 (i.e., all carbon that is not directly emitted as CO_2 from the mill to the atmosphere). The carbon contents of the different input and output streams to the mill were assumed according to Table A4.

Table A3
Technical parameters for the carbon capture module.

Symbol	Parameter	Unit	Value
r	CO_2/fuel ratio	tCO_2/tonne fuel	Recovery boiler: 1.17 Bark boiler: 1.85 Lime kiln: 2.66
f_{lm}	Loading mass factor	tonne solvent/tCO_2	5.13

Table A4
Carbon contents of the different input and output streams to the mill.

Feedstock/product	Carbon content (%)
Softwood, wood chips, bark	50
Pulp	42
Lignin	57
Carbon dioxide	27

Data availability

Data will be made available on request.

References

[1] European parliament and the EU council, Regulation (EU) 2021/1119 of the European parliament and of the council, Off. J. Eur. Union (2021). L 243/1.
[2] J. Hansson, E. Fridell, S. Brynolf, E. Malmgren, M. Grahn, K. Andersson, "Framtida bränsleval för flyg. Sjöfart Och Vägtransporter Ur Ett Energisystemperspektiv - Analys Av Kostnadseffektivitet Och Andra Viktiga Kriterier Vid Bränsleval Samt Elektrobränslens Miljöpåverkan, 2022.
[3] F. Johnsson, K. Möllersten, L. Zetterberg, "Towards net-zero emissions – how can carbon dioxide capture and storage contribute? SNS Analysis 98 (2023).
[4] ÅForsk, Energy Consumption in the Pulp and Paper Industry - Model Mills 2010, 2011.
[5] P. Tomani, The LignoBoost process, Cellul. Chem. Technol. 44 (1–3) (2010) 53–58.
[6] M.R. Olsson, E. Axelsson, T. Berntsson, Exporting lignin or power from heat-integrated kraft pulp mills: a techno-economic comparison using model mills, Nord. Pulp Pap Res. J. 21 (2006).
[7] P. Tomani, P. Axegård, N. Berglin, A. Lovell, D. Nordgren, Integration of lignin removal into a kraft pulp mill and use of lignin as a biofuel, in: 5th International Colloquium on Eucalyptus Pulp, 2011.
[8] M. Benali, et al., Implementation of lignin-based biorefinery into a Canadian softwood kraft pulp mill: optimal resources integration and economic viability assessment, Biomass Bioenergy 67 (Aug. 2014) 473–482, https://doi.org/10.1016/J.BIOMBIOE.2013.08.022.

[9] C.G. Culbertson Jr., Commercialization of Sustainable Bio-Refinery Projects for the Pulp & Paper Industry, 2017.
[10] K. Onarheim, S. Santos, P. Kangas, V. Hankalin, Performance and costs of CCS in the pulp and paper industry part 1: performance of amine-based post-combustion CO2 capture, Int. J. Greenh. Gas Control 59 (Apr. 2017) 58–73, https://doi.org/10.1016/J.IJGGC.2017.02.008.
[11] K. Onarheim, S. Santos, P. Kangas, V. Hankalin, Performance and Cost of CCS in the Pulp and Paper Industry Part 2: Economic Feasibility of Amine-Based Post-combustion CO 2 Capture, 2017, https://doi.org/10.1016/j.ijggc.2017.09.010.
[12] K. Kuparinen, S. Lipiäinen, E. Vakkilainen, T. Laukkanen, Effect of biomass - based carbon capture on the sustainability and economics of pulp and paper production in the Nordic mills, Environ. Dev. Sustain. 25 (1) (2023) 648–668, https://doi.org/10.1007/s10668-021-02074-9.
[13] F. Nilsson, Evaluation of Excess Heat Driven Carbon Capture Integrated at a Swedish Pulp Mill, 2023.
[14] H. Skoglund, C. Fu, S. Harvey, E. Svensson, Integration of Carbon Capture in a Pulp Mill-Effect of Strategic Development towards Better Biomass Resource Utilization, 2023, https://doi.org/10.3389/fther.2023.1282028.
[15] S. Ingvarsson, M. Odenberger, F. Johnsson, The chemical pulp mill as a flexible prosumer of electricity, Energy Convers. Manag. X 20 (Oct. 2023) 100401, https://doi.org/10.1016/J.ECMX.2023.100401.
[16] S. Ingvarsson, M. Odenberger, F. Johnsson, Lignin extraction in chemical pulp mills : the role of flexible operation, Sustain. Chem. Environ. 7 (July) (2024) 100137, https://doi.org/10.1016/j.scenv.2024.100137.
[17] D.S. Bajwa, G. Pourhashem, A.H. Ullah, S.G. Bajwa, A concise review of current lignin production, applications, products and their environment impact, Ind. Crops Prod. 139 (June) (2019) 111526, https://doi.org/10.1016/j.indcrop.2019.111526.
[18] S. V Obydenkova, P.D. Kouris, E.J.M. Hensen, H.J. Heeres, M.D. Boot, Environmental economics of lignin derived transport fuels, Bioresour. Technol. 243 (2017) 589–599, https://doi.org/10.1016/j.biortech.2017.06.157.
[19] International Energy Agency (IEA). Putting CO2 to Use: Creating Value from Emissions, 2019, p. 44.
[20] P. Oeuvray, J. Burger, S. Roussanaly, M. Mazzotti, V. Becattini, Multi-criteria assessment of inland and offshore carbon dioxide transport options, J. Clean. Prod. 443 (June 2023) 140781, https://doi.org/10.1016/j.jclepro.2024.140781, 2024.
[21] J. Kjärstad, R. Skagestad, N.H. Eldrup, F. Johnsson, Ship transport—a low cost and low risk CO2 transport option in the Nordic countries, Int. J. Greenh. Gas Control 54 (2016) 168–184, https://doi.org/10.1016/j.ijggc.2016.08.024.
[22] IEA, Renewables 2020, 2020. Paris.
[23] International Renewable Energy Agency (IRENA), Innovation Outlook: Renewable Methanol, 2021.
[24] M. Pahle, J. Sitarz, O. Sebastian, G. Benjamin, The EU-ETS Price through 2030 and beyond: A Closer Look at Drivers, Models and Assumptions, November, 2022.
[25] F. Simon, "EU carbon price to hit €400 mark with 90% climate goal: analysts," Euractiv. Accessed: June. 14, 2024. [Online]. Available: https://www.euractiv.com/section/emissions-trading-scheme/news/eu-carbon-price-to-hit-e400-mark-with-90-climate-goal-analysts/.
[26] Enerdata, "Carbon price forecast under the EU ETS." [Online]. Available: https://www.enerdata.net/publications/executive-briefing/carbon-price-projections-eu-ets.html.
[27] S. Öberg, L. Göransson, H.E. Fälth, U. Rahmlow, F. Johnsson, Evaluation of Hydropower Equivalents in Energy Systems Modeling, 2024. *Unpublished*.
[28] M. Biermann, F. Normann, F. Johnsson, R. Skagestad, Partial carbon capture by absorption cycle for reduced specific capture cost, Ind. Eng. Chem. Res. 57 (45) (Nov. 2018) 15411–15422, https://doi.org/10.1021/ACS.IECR.8B02074.
[29] S. Ingvarsson, M. Odenberger, and F. Johnsson, "Lignin extraction in chemical pulp mills: the role of flexible operation," Sustain. Chem. Environ...
[30] A.J. Robinson, et al., Techno-economic optimization of a process superstructure for lignin valorization, Bioresour. Technol. 364 (August) (2022) 128004, https://doi.org/10.1016/j.biortech.2022.128004.
[31] Ember Climate, Carbon price tracker [Online]. Available: https://ember-climate.org/data/data-tools/carbon-price-viewer/. (Accessed 8 August 2024).
[32] Y. Jafri, Biofuels from kraft black liquor pilot-scale gasification development and techno-economic evaluation of industrially relevant biofuel production pathways [Online]. Available: www.ltu.se, 2019. (Accessed 1 July 2021).
[33] M. Woerner, U. Hornung, and N. Dahmen, "HYDROTHERMAL LIQUEFACTION OF BLACK LIQUOR.".
[34] F. Johnsson, F. Normann, E. Svensson, Marginal abatement cost curve of industrial CO2 capture and storage – a Swedish case study, Front. Energy Res. 8 (Aug) (2020), https://doi.org/10.3389/fenrg.2020.00175.
[35] European parliament and the EU council, Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the Use of Renewable and Low-Carbon Fuels in Maritime Transport, and Amending Directive 2009/16/EC, 2023.
[36] Naturvårdsverket, "Utrikes sjöfart och flyg, utsläpp av växthusgaser." [Online]. Available: https://www.naturvardsverket.se/data-och-statistik/klimat/vaxthusgaser-utslapp-fran-utrikes-sjofart-och-flyg/.
[37] European Commission, Fourth Annual Report from the European Commission on CO2 Emissions from Maritime Transport (Period 2018-2021), 2023, p. 74.
[38] ERM, Assessment of European Biogenic CO2 Balance for SAF Production, 2022.
[39] European parliament, POSITION OF THE EUROPEAN PARLIAMENT EP-PE_TC1-COD, 2021 0211A, 2023.
[40] F. Johnsson, K. Möllersten, L. Zetterberg, "Mot nettonollutsläpp – hur kan koldioxid avskiljning bidra? SNS Analys 98 (2023) no. november.
[41] J. Hu, E.O. Jåstad, T.F. Bolkesjø, P.K. Rørstad, Impact of large-scale Bio-CCS deployment on forest biomass competition and forest industry production, Biomass Bioenergy 175 (Aug. 2023) 106896, https://doi.org/10.1016/J.BIOMBIOE.2023.106896.
[42] E. Svensson, S. Harvey, H. Skoglund, ACCSESS D5.2 CO2 Capture Integration Scenarios and Process Modelling Due, 2023.
[43] V. Ignell, E. Johansson, Local Infrastructures for CCS Clusters A Case Study of Two CHP Plants in Gothenburg, 2021.
[44] E. Fahrman, S. Harvey, and F. Normann, "Pre-study for the Implementation of Carbon Capture at Boliden Rönnskär Influence of Batch Operation and Opportunities for Integration with the Existing Energy System.".