Can carbon capture be a new revenue opportunity for the pulp and paper sector?

KATJA KUPARINEN, SATU LIPIÄINEN, AND ESA VAKKILAINEN

ABSTRACT: Transition towards carbon neutrality will require application of negative carbon emission technologies (NETs). This creates a new opportunity for the industry in the near future. The pulp and paper industry already utilizes vast amounts of biomass and produces large amounts of biogenic carbon dioxide. The industry is well poised for the use of bioenergy with carbon capture and storage (BECCS), which is considered as one of the key NETs. If the captured carbon dioxide can be used to manufacture green fuels to replace fossil ones, then this will generate a huge additional market where pulp and paper mills are on the front line.

The objective of this study is to evaluate future trends and policies affecting the pulp and paper industry and to describe how a carbon neutral or carbon negative pulp and paper production process can be viable. Such policies include, as examples, price of carbon dioxide allowances or support for green fuel production and BECCS implementation. It is known that profitability differs depending on mill type, performance, energy efficiency, or carbon dioxide intensity. The results give fresh understanding on the potential for investing in negative emission technologies. Carbon capture or green fuel production can be economical with an emission trade system, depending on electricity price, green fuel price, negative emission credit, and a mill's emission profile. However, feasibility does not seem to evidently correlate with the performance, technical age, or the measured efficiency of the mill.

Application: This study gives fresh understanding on the potential for investing in negative emission technologies and green fuel production in the pulp and paper industry; thus, the results may be interesting to industrial operators and policymakers.

As humans seek ways to limit the rise in global temperature, capturing carbon dioxide (CO_2) emissions from biomass burning and permanently storing these emissions appears one potential way to create the necessary negative CO_2 emissions. As the pulp and paper industry is already the largest industrial bioenergy user, it is well positioned to apply carbon capture and utilization or storage (CCUS) [1]. Kraft pulp mills produce renewable energy from biomass with their recovery boilers, which represent one of the world's largest segments of biomass boilers [2]. In most mills, an additional biomass boiler combusts bark and other wood residues, generating even more bioenergy. On average, a European kraft pulp mill emits over 0.5 metric tons of biogenic CO_2 per year [3]. The global technical carbon capture potential from kraft pulp mills has been estimated at approximately 137 megatonnes of CO_2 (Mt_{CO2}) per year [4]. Therefore, kraft pulp mills offer a significant potential for implementation of both bioenergy with carbon capture and storage (BECCS) and bioenergy with carbon capture and utilization (BECCU).

BECCS is considered as one of the key negative emission technologies (NETs). BECCS leads to negative emissions when carbon from sustainably grown biomass is captured and permanently stored. Large pulp and paper production units enable BECCS implementation in the existing processes without additional land use or biomass harvesting. The pulp and paper industry is a diverse industrial sector with high energy intensity and a high share of bioenergy. If BECCS is used in kraft pulp mills, the fossil CO_2 emissions are often small enough to make the mill a carbon sink, even with a low carbon capture rate [4]. Onarheim et al. [5] estimated that a negative emissions credit of 60–80 EUR/metric ton_{CO2} (approximately 75–95 USD/metric ton_{CO2}) would be needed for a profitable CCS implementation at a kraft pulp mill. The costs are lower for a standalone mill and higher for an integrated mill. Using BECCU, a mill could utilize captured CO_2 for production of renewable biofuels or chemicals for sale [6], thus widening its product portfolio. As there are secondary steam and low temperature heat streams in pulp mills that can be utilized, there are additional financial benefits. Renewable fuels and chemicals production from captured biobased CO_2 does not always decrease atmospheric CO_2, but it delays CO_2 release. If the products are used to replace fossil ones, they indirectly decrease CO_2 in the atmosphere.

A European long-term vision [7] aims at net-zero greenhouse gas (GHG) emissions by 2050. The European Green Deal provides an action plan towards the target, naming CCUS as one of the industrial priority areas [8]. A sustainable energy system has a key role, since 75% of the GHG emissions originate from energy supply in the EU. The main policy instrument is the emission trading system (ETS), which considers only fossil CO_2 [9]. The lack of political prioritization, followed by the lack of policy incentives, is currently seen as the main barrier preventing investments in BECCS [10]. In the United States, no federal level mandate is yet in use, but industrial operators need to react to the developing legislation and limitations aimed at emission reduction. The U.S. long-term low greenhouse gas emission development strategy under the United Nations Framework Convention on Climate Change (UNFCCC) includes industrial CCUS [11]. A recent report on "Net-Zero America" from Princeton University [12] calls for biomass industry to utilize BECCS, electrolysis, and/or methane reforming to revolutionize the energy sector by 2050. For example, in California, a cap-and-trade program is a key element of the state's strategy to cost-effectively reduce GHG emissions and meet set emission targets [13]. The program is an emission trade system and largely similar to the EU ETS program in that it creates an annually reduced amount of allowances for permissible emissions.

Viable CO_2 utilization as a raw material requires creation of an economical operational environment for the new technologies and products. Bulk products, such as fuels, compete in the market with their fossil alternatives and are likely to need legislative support in the form of mandates or subsidies to gain ground [6]. Carbon capture and low carbon fuels both play a notable role in the transition to a low carbon or carbon reuse economy. Their feasibility can be improved by several measures, including taxation, emissions trade schemes, and financial support for capital investment. Capital costs play a notable role in CCS projects [14].

In this paper, energy consumption data on different types of mills is used to find out what kinds of incentives are needed to make BECCS or green fuel production economical in the existing pulp and paper industry. The paper aims at finding out when the revenue from generated CO_2 or produced fuel per metric ton of product exceeds the cost of applying the new processes. The results of the paper advance the knowledge on the effects of BECCS/BECCU implementation in different types of pulp and paper mills and clarify what combination of cost factors and mill operational features promotes investments in BECCS/BECCU, while also considering the effect of carbon pricing. Even though the revenue from biogenic CO_2 generation might be significant, the economic lifeline for the pulp and paper industry remains production of paper and paperboard.

METHODS AND MATERIALS

Mill data and classification

Energy consumption and its allocation to products (pulp, paper, or paperboard) in different types of Nordic pulp and paper industry units was earlier studied [15], and the collected statistical data was updated for a previous study [16] using recent references [17,18] and CO_2 emission statistics [19]. The data was originally collected in 2018–2019 and updated in 2020 using the most recent references. Company and unit specific data collection, more than one company operating on the same site, and energy generation both for sale and for a company's own use create challenges in compiling comparable data. The effect of uncertainties in the statistical data was minimized by using careful consideration and the choice of studied mills [20]. The selection of mills for this study was then chosen based on the objective to both include a wide selection of mill types and ensure the accuracy of the used data. Data collection and its limitations are discussed in more detail in earlier studies [15,16].

The mill types included in this study were intentionally diverse: market kraft pulp, supercalendered/lightweight coated (SC/LWC) paper, integrated fine paper, newsprint, and testliner [16]. **Table I** shows these categories and introduces the mills within the categories. These mill types account for the majority of mills in the Nordic countries. The studied mills annually produce 9.7 million metric tons of pulp and 7.4 million metric tons of paper/board, and thus accounted in 2019 for approximately 21% of pulp production and 7% of paper/board production in Europe [21]. The mills were further grouped into good, average, and low performers within the categories based on industrial experience. The score in the performance category implies overall performance and is not associated with, for example, fossil fuel usage. The studied mills have widely differing energy economics; namely, the specific electricity and heat consumption for the same product vary. Most of them produce chemical (kraft) pulp, but smaller amounts of mechanical or semichemical pulp or recycled fiber is also produced and/or used. Many mills produce more than one product, and their energy portfolio is diverse. The main fossil fuel used is heavy fuel oil (HFO) or natural gas (NG). Many mills use smaller amounts of other fossil fuels, such as light fuel oil (LFO), coal, peat, and propane. Integrated mills include mills that operate on the same site, even when legally operated by separate companies.

Energy efficiency can be defined as the ability to produce high amounts of product using a small amount of energy. Improved energy efficiency is likely to decrease production costs. However, energy efficiency does not necessarily correlate with the economic performance of the mill, because the economic performance depends on many factors in addition to energy efficiency. Improved energy efficiency also leads, in general, to a decrease in specific CO_2 emissions, but an energy-efficient mill is not necessarily CO_2 efficient due to different products, process alternatives, and mill configurations. Stenqvist and Åhman [22] also noticed that benchmark-based allowance allocation, such as in the EU ETS, does not result in the best performance in sectors like the pulp and paper industry due to concentrating on specific energy consumption (SEC) instead of emission intensity. Therefore, in addition to SEC, we calculated the CO_2 emission intensity ($kgCO_2$/metric $ton_{product}$) for the studied mills [16]. Earlier studies [15,23] present the principles used for the allocation of energy consumption and calculating the energy efficiency and emission intensity. The used CO_2 emission factors and lower heating values (LHVs) of the fuels are based on references [23–25]. The specific energy and emission figures were cal-

Group	Mill Name	Economic Performance	Integrated Mill	Main Fossil Fuel
Market kraft pulp mill	Pulp1	good	yes	Bio[1]
	Pulp2	average	no	HFO
	Pulp3	average	no	HFO
	Pulp4	average	no	Bio[1]/NG
	Pulp5	low	no	NG
SC/LWC paper mill	MagzP1	good	yes	NG
	MagzP2	average	yes	HFO
	MagzP3	low	yes	NG
Integrated fine paper mill	FineP1	good	yes	HFO
	FineP2	average	yes	NG
	FineP3	low	yes	HFO
Testliner mill	TestL1	good	yes	NG
	TestL2	average	yes	HFO
	TestL3	average	yes	HFO
	TestL4	low	yes	HFO
Newsprint mill	NewsP1	good	yes	HFO
	NewsP2	low	yes	HFO

SC/LWC = supercalendered/lightweight coated; HFO = heavy fuel oil; NG = natural gas.
[1] The mill uses biofuels to notably substitute for typical fossil fuel use.

I. Mill classification and the studied mills.

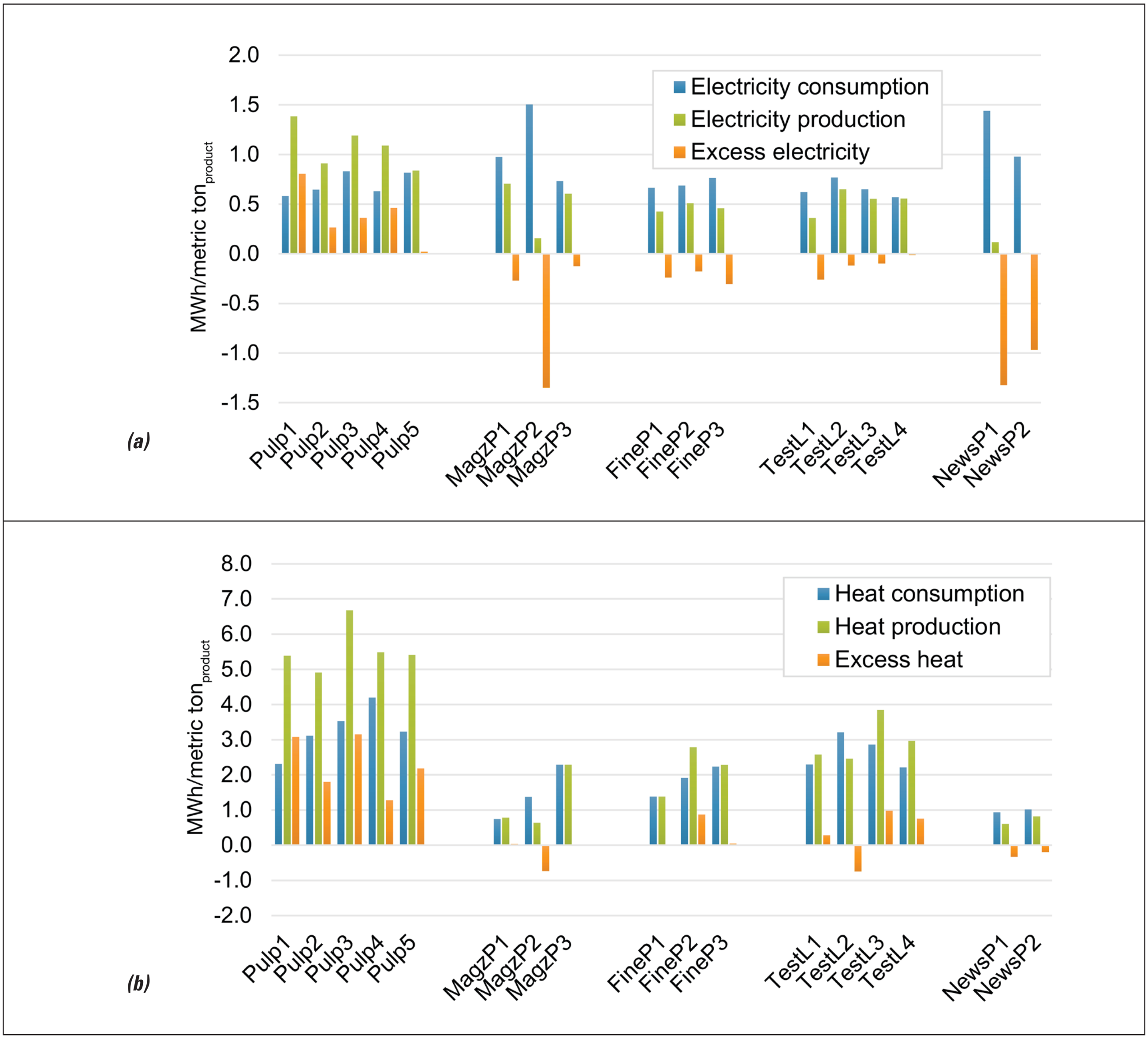
culated for pulp and paper combined, despite that, in integrated mills, part of pulp is commonly used on site in paper or board production.

Figure 1 presents the specific electricity and heat balances of the studied mills. The figure shows that the studied market kraft pulp mills are energy-independent and even produce excess power and heat. In the other mill groups, meeting the electricity demand typically requires purchase, and heat production is commonly adjusted to their own use by additional production, considering the secondary heat from electricity use.

Figure 2 presents the CO_2 emission intensity, as well as the share of fossil CO_2 emissions calculated from the total emissions for the studied mills. The CO_2 emissions include the usage of all fossil and biobased fuels, along with biobased side streams combusted on site. Emission intensity is related to the energy efficiency of the mill and the choice of fuels because they have varying emission factors. Efficiency and fuel choices vary greatly between the studied mills. Figure 2 shows that the lowest share of fossil fuels is in the market kraft pulp mill and the testliner mill groups, and the highest is in the SC/LWC paper mill and newsprint mill groups. The figure also highlights the clear differences between individual mills, even in the same group. These differences do not seem to correlate with the economic performance of the mills.

Carbon capture in pulp and paper industry units

Capture of biogenic CO_2 from the outgoing flows of a pulp and paper mill is a little studied subject [26], but recent studies have found it technically feasible [4,27]. The largest CO_2 point sources in a pulp mill are the combustion processes: the recovery boiler, the lime kiln, and the biomass boiler. Several capture methods — such as pre-combustion, post-combustion, and oxy-combustion methods — can be applied at pulp and paper mills. Many of these are in the development stage. The commercial monoethanolamine (MEA) process [26,28,29] is the most studied capture method and was chosen as the reference method in this study. As a post-combustion method, it can be easily applied to existing mills. The efficiency of the MEA process is at around 80%–90%. The MEA process uses electricity and

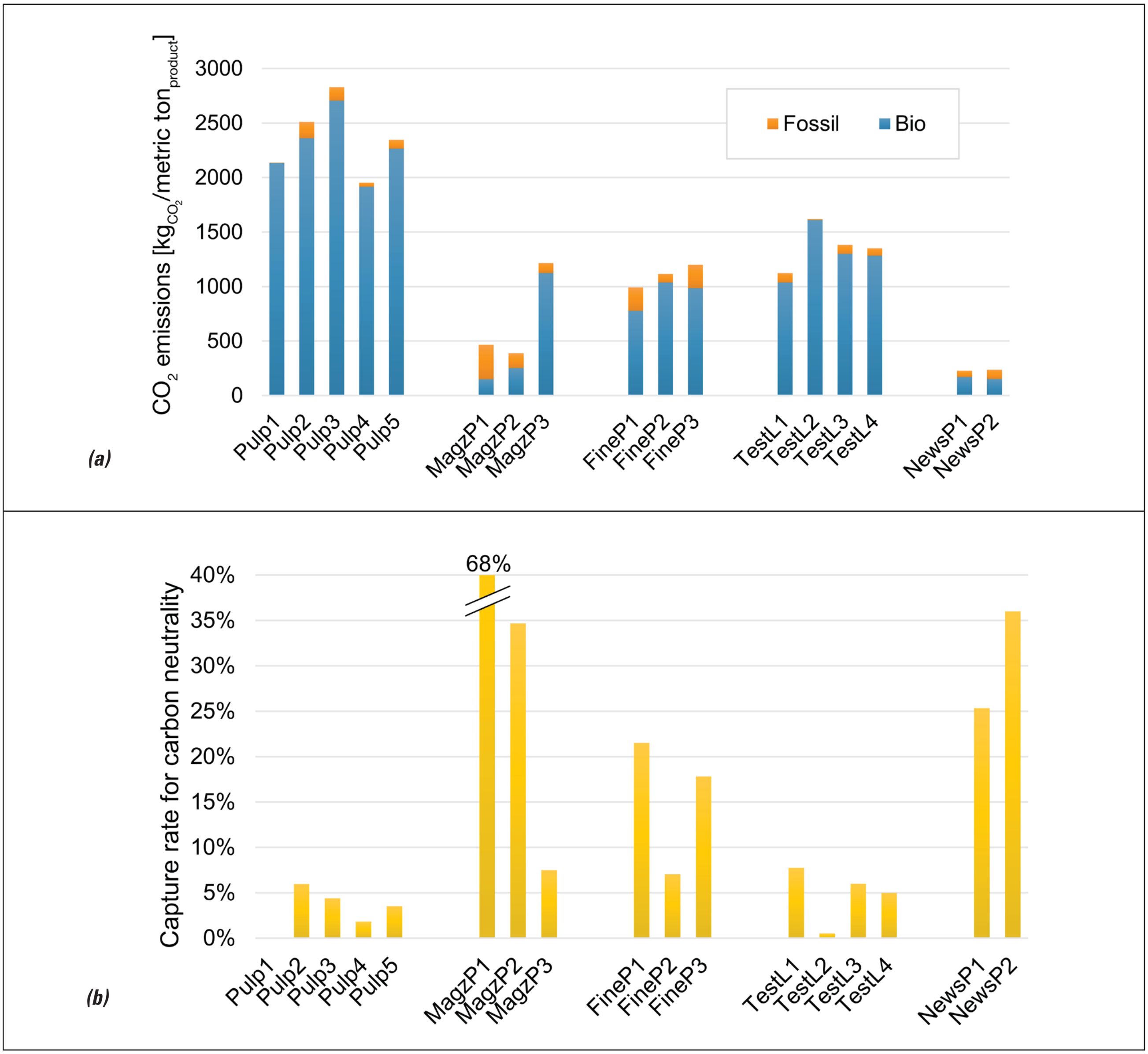


1. Specific electricity (a) and heat (b) balances for the studied mills.

steam, therefore affecting the energy balance of the mill [28]. While a modern kraft pulp mill often produces electricity and steam in excess of its own needs [30], an integrated mill typically requires additional energy generation if processes such as carbon capture are added. The heat use for sorbent regeneration used in this study for the MEA process is 3.7 MJ/kg_{CO2}. Based on earlier estimates, the cost of CO_2 avoided in pulp mills ranges at approximately 25–110 USD/metric ton_{CO2}, depending on the chosen processes and mill details [27,31].

Green hydrogen production

Water electrolyzers decompose water into hydrogen and oxygen using electricity. If the electricity source is renewable, then green hydrogen is produced. Alkaline electrolysis (AE) is the most mature electrolysis technology [32] and is the chosen reference method in this study. The operating temperature of an alkaline electrolyzer is typically at 60°C–80°C. Its efficiency is at 60%–80% based on the higher heating value of hydrogen [33]. Expert estimation of the capital costs for a 10 MW AE system was at 850–1700 USD/kW for the year 2020 [34]. An alkaline electrolyzer produces residual heat at temperatures of 70°C–90°C, which can be utilized. Pulp mills often have abundantly low temperature heat available; therefore, revenue from residual heat was not considered in this study. The AE integration has the additional benefit of producing pure oxygen, which is typically needed in the pulping process, such as for bleaching. Electrolyzer integration can then make separate oxygen production or purchase unnecessary [35]. The oxygen demand of a kraft pulp mill equals to around 10%–15% of the power generation of the mill using the electrolyzer.



2. Specific biogenic and fossil CO_2 emissions (a) and the needed capture rate for carbon-neutral production from the total CO_2 emissions (b) for the studied mills.

Green transport fuel production

The industry and transport sectors are in many ways dependent on carbon-based fuels and commodities. Green fuels offer the possibility to replace fossil fuels where the physical and chemical properties of fuels are essential and emission reduction using other means, such as electrification, is difficult. The most widely proposed utilization for captured biogenic CO_2 is to generate synthetic hydrocarbons using green hydrogen [6]. Carbon-neutral electrofuels (e-fuels) can then be produced if electricity is renewable and biobased CO_2 is sustainable [7]. Methanol (MeOH) synthesis was chosen here as the reference green fuel technology, because it is a more mature technology than many other carbon dioxide-based synthesis processes [6]. Methanol also has large markets, because in addition to fuel use, it is widely used in the chemical industry for many other products, such as formaldehyde, methyl tert-butyl ether (MTBE), and acetic acid [36]. The predominant methanol production method is catalytic conversion of synthesis gas derived mainly from natural gas.

Methanol can be directly produced from CO_2 using a hydrogenation process [36]. The reaction is exothermic and can supply about one-third of the heat required in the carbon capture process. Based on the LHVs of hydrogen and methanol, the efficiency of the synthesis is 83% [37]. If the efficiency for AE based on the LHV of hydrogen is 67%, the overall efficiency from water to methanol is 56%.

Case	ETS Price, USD/metric ton$_{CO2}$	Negative Emission Credit, USD/metric ton$_{CO2}$	Carbon Capture Rate, %	CO_2 for MeOH, % of captured	Electricity Sale Price, USD/MWh	Electricity Purchase Price, USD/MWh
ETS	35	-	-	-	-	-
CapLow	35	-	15	-	-	-
CapMed	85	85	15	-	-	-
CapHigh	85	85	50	-	-	-
MetLow	35	-	15	20	48	80
MetMed	85	85	15	20	24	40
MetHigh	85	85	50	100	24	40
ETS = emission trading system; CO_2= carbon dioxide; MeOH = methanol.						

II. The studied cases.

Basis for cost calculations

The aim of the cost calculations is to estimate how the cost of carbon capture and green fuel production could be recovered. The technical evaluation of carbon capture, electrolysis, and methanation is based on the process descriptions presented in their previous respective sections. The effect of the following factors on the production costs with a BECCS/BECCU application was studied:

- Emission trading system price
- Negative emissions credit
- Electricity cost for electrolysis
- Mill economic performance (good/average/low)
- Carbon capture rate

Carbon capture cost was estimated at 75 USD/metric ton$_{CO2}$ based on recent studies [26,27,29], including energy costs. The cost of methanol production, including electrolysis, was estimated at 360 USD/metric ton based on Bos et al. [38], excluding the electricity cost for electrolysis. Methanol spot prices in the United States have been varying between 150 and 430 USD/metric ton during 2018–2020, with the average being roughly 320 USD/metric ton [39]. The price has been on the rise recently. For renewable methanol, the price can be expected to be higher. In this study, fossil methanol price of 380 USD/metric ton and a premium factor of 1.5 were assumed, resulting in a renewable methanol sale price of 570 USD/metric ton. Operation time of 8400 h/year was assumed for all mills and cases. In addition to the change in the production cost of pulp and paper, a marginal negative emission credit and a marginal methanol sale price are calculated to give the level of credit or price that covers the expenses of new processes in each case.

Table II presents the studied cases and the variables used. The cases are compared to a base case, where the emission allowances are allocated with no cost and no BECCS/BECCU is applied. The variables are ETS price, negative emission credit, carbon capture rate, the share of captured CO_2 used for methanol production, and the electricity price for cases, including electrolysis. Carbon capture rate represents the amount of captured CO_2 from the total emissions of the mill, including both fossil and biogenic CO_2. The ETS price was estimated based on recent developments with market prices for emissions allowances [13,40]. A negative emissions credit was based on the assumption that CO_2 capture will be credited in the future [41]. For electricity price estimation, recent price development in the United States and Europe was reviewed [42, 43]. Electricity sale price and purchase price are estimated separately, as some mills can at least partly use their own production to cover the electricity needed for electrolysis.

Case ETS in Table II presents a case where an ETS price is allocated to all fossil fuel-based CO_2 emissions for the mill, but no carbon capture is applied. Cases CapLow, CapMed, and CapHigh in Table II present the situation where CO_2 is captured but not utilized. In these cases, ETS price, negative emission credit, and carbon capture rate vary, and electricity for the capture process is included in the estimated capture cost. In the cases MetLow, MetMed, and MetHigh, varying amounts of captured carbon is utilized for methanol production, and the profitability of the cases is estimated by varying the ETS price, negative emission credit, and electricity price for electrolysis.

RESULTS AND DISCUSSION

The results aim at clarifying what combinations of carbon pricing, methanol price, energy efficiency, emission intensity, and mill economic competitiveness will promote investments in carbon capture and green fuel production; how an increased ETS price or negative emission credit affect to the market price of pulp and paper mill products; and how the situation varies with the mill type and performance. The calculations show possible effects of the studied processes. Mill-specific details and local conditions determine whether an investment is feasible in a real case. All

	Mill	ETS	CapLow	CapMed	CapHigh
Market kraft pulp mill	Pulp1	0	24	-3	-11
	Pulp2	5	28	9	0
	Pulp3	4	32	6	-4
	Pulp4	1	22	0	-7
	Pulp5	3	26	4	-5
SC/LWC paper mill	MagzP1	11	14	26	25
	MagzP2	5	7	11	10
	MagzP3	3	14	6	2
Integrated fine paper mill	FineP1	7	13	17	13
	FineP2	3	13	5	1
	FineP3	7	15	16	12
Testliner mill	TestL1	3	13	6	2
	TestL2	0	18	-2	-7
	TestL3	3	16	5	0
	TestL4	2	15	4	-1
Newsprint mill	NewsP1	2	3	5	4
	NewsP2	3	4	7	6

III. Change in production cost (USD/metric ton$_{product}$) in ETS and carbon capture cases compared with the base case where the emission allowances are allocated with no cost.

prices and costs are estimations based on public data and will be different in actual practice. Therefore, these results are to be considered indicative only, and each mill case should be estimated and evaluated separately.

Effect on production costs

Table III presents the changes in the production costs of pulp and paper for the ETS case and the carbon capture cases CapLow, CapMed, and CapHigh. **Table IV** correspondingly presents the methanol cases MetLow, MetMed, and MetHigh. ETS price for fossil CO_2 emissions has a higher impact for the mills where the fossil fuel-based emissions are the highest. A moderate ETS price assumed in the ETS case causes, at highest, an increase of 11 USD/metric ton$_{product}$. In most mills, the cost increase is low, below 5 USD/metric ton$_{product}$. The lowest cost increases per metric ton of product can be found in the testliner mill and market pulp mill groups. In the methanol cases, the methanol production costs exceed the income from sale; only mill Pulp1 in case MetMed can cover the costs with the given negative emission credit. It should be noted that the specific costs are calculated for both pulp and paper to keep the figures comparable; for integrated mills, the cost increase would be higher if it was calculated for only the main product.

The market price of northern bleached kraft pulp increased in the beginning of 2021 at about 1100 USD/metric ton [44], which means that in the ETS case for the market kraft pulp mill group, the average production cost increase accounts for 0.2% of the market price. Correspondingly, the effects of carbon capture in cases CapLow, CapMed, and CapHigh are, on average, 2.4%, 0.3%, and -0.5% of market price for the market kraft pulp mills.

Effect of negative emission compensation

Carbon capture processes are technically feasible when applied to pulp and paper production, but economic feasibility requires income to cover the costs of the investment and operation. When fossil fuel-based CO_2 is captured, the mill operators benefit if they need to purchase less emission allowances. For biobased emissions, a negative emissions credit or sufficient income from CO_2-based products is needed to cover the costs of CO_2 capture.

The carbon capture cases show that a high negative emissions credit, such as used in the cases CapMed and CapHigh, is needed to make carbon capture profitable (Table III). **Table V** highlights this by presenting a mar-

	Mill	MetLow	Met Med	MetHigh
Market kraft pulp mill	Pulp1	36	-2	110
	Pulp2	50	14	153
	Pulp3	54	11	168
	Pulp4	33	1	108
	Pulp5	54	12	142
SC/LWC paper mill	MagzP1	19	28	54
	MagzP2	12	12	34
	MagzP3	28	10	78
Integrated fine paper mill	FineP1	25	20	75
	FineP2	26	9	71
	FineP3	29	21	87
Testliner mill	TestL1	26	10	72
	TestL2	38	4	94
	TestL3	32	10	87
	TestL4	31	9	84
Newsprint mill	NewsP1	6	5	18
	NewsP2	7	8	21

IV. Change in production cost (USD/metric ton$_{product}$) in the methanol cases compared with base case where the emission allowances are allocated with no cost.

ginal negative CO_2 credit, namely, the price for negative CO_2 that would be needed to keep the production costs unchanged when carbon capture or methanol production is applied. Case CapMed is excluded, because due to same capture rate, it gives the same values as CapLow. The empty cells in the table indicate that the used capture rate is lower than the share of fossil-fuel based CO_2 emissions; in these cases, the mills do not reach negative emissions. The results show that market kraft pulp mills have the highest potential to apply the new processes, followed by testliner mills. However, the required marginal compensation for negative emissions is relatively high. The average marginal compensation for market kraft pulp mills is at 98 and 80 USD/metric ton$_{CO2}$ in CapLow and CapHigh, respectively. Similarly, the average values for testliner mills are 118 and 83 USD/metric ton$_{CO2}$.

Revenue opportunities from green fuel sale

Green fuel production increases costs but brings additional benefits in the form of a new sellable product. The relevant question is: when do the profits exceed costs? The results in Table IV point out that this requires a high negative emission compensation or a very low electricity price if the methanol price is at the assumed level. Table V shows that for the methanol cases, the average marginal negative CO_2 credit is over 100 USD/metric ton$_{CO2}$ in all mill groups; the lowest average value is 113 USD/metric ton$_{CO2}$ for the market pulp mill group in the case MetMed. The results also highlight that when a larger part of captured carbon is converted to methanol, the electricity cost exceeds the income from methanol sales and negative emissions. A higher methanol sale price would compensate for this. Other paths to an economically feasible production process are low electricity prices or cheap hydrogen from another source, or even higher compensation for negative emissions than the one used in this study. Marginal methanol price was calculated to determine the methanol price level needed to cover the production costs, including carbon capture (**Table VI**). The lowest value, 522 USD/metric ton, can be found for mill Pulp1 in the case MetMed, where negative emission compensation is high, electricity price is low, and less CO_2 is converted to methanol than in MetHigh. This price is close to the possible market price previously estimated for renewable methanol, 570 USD/metric ton, including a green premium.

The varying energy economics and emission intensity

	Mill	CapLow	CapHigh	MetLow	MetMed	MetHigh
Market kraft pulp mill	Pulp1	75	75	111	78	188
	Pulp2	125	85	219	148	224
	Pulp3	106	82	180	122	215
	Pulp4	85	78	126	89	200
	Pulp5	98	81	199	130	215
SC/LWC paper mill	MagzP1	-	-	-	-	-
	MagzP2	-	245	-	-	654
	MagzP3	150	88	309	200	236
Integrated fine paper mill	FineP1	-	132	-	-	352
	FineP2	142	87	292	189	233
	FineP3	-	117	-	-	311
Testliner mill	TestL1	155	89	320	207	237
	TestL2	78	76	160	104	203
	TestL3	125	85	257	167	228
	TestL4	112	83	232	150	223
Newsprint mill	NewsP1	-	152	-	-	406
	NewsP2	-	268	-	-	716

V. Marginal negative CO_2 credit (USD/metric ton_{CO2}) for each case. An empty cell indicates that the capture rate is lower than the share of fossil CO_2 emissions (i.e., negative emissions are not reached).

make evaluation of feasibility of the cases complicated. Both capture rate and the share of captured CO_2 that is used for methanol production significantly affect the feasibility. Most cases are calculated using relatively low capture rates, 15% of the total CO_2 from the mills. Pulp mills have several CO_2 outflows, of which the largest is typically the recovery boiler. It is likely more economical to apply the capture process to the largest CO_2 flow(s) instead of all the possible ones. Despite the benefits economies of scale might bring, it is highly dependent on local conditions as to whether it is possible to apply a BECCS/BECCU process to more than a minor part of a mill's CO_2 emissions. Large amounts of CO_2 for storage or reuse raise questions about logistics, storage possibilities, and/or green product markets. Higher capture rate followed by conversion to fuels might even increase the specific costs, depending on the mill and the initial values, as the results show. High capture and conversion rate, however, also equalizes the differences between the mills, as can be seen when comparing cases MetMed and MetHigh in Table VI.

Methanol is widely used as a chemical feedstock and transportation fuel. Methanol use is on the increase, and in the future, biomethanol demand is likely to grow even more due to growing interest in fossil-free products. The global methanol production capacity was around 150 million metric tons in 2020, while the demand was at around 98 million metric tons [35]. Pulp mill CO_2 flows have a significant potential to respond to the increasing demand for methanol. **Table VII** presents the annual methanol production for the studied mills in the cases MetLow and MetHigh. With 50% of CO_2 emissions used for methanol conversion, as in the MetHigh case, the studied market kraft pulp mills together would be able to cover nearly 2.7% of the current global methanol demand. Including all the studied mills increases this number to 7.5%.

Emission reduction in the pulp and paper industry

The pulp industry has the potential to significantly contribute to CO_2 emissions reduction, both as a large user of bioenergy in particular and due to significant fossil and bio-based CO_2 emissions. This leads to the question as to the choice of methods for reducing these emissions. The question should be interesting to both industrial operators and policymakers. Recent scenarios state that nearly carbon-neutral production can be achieved in the Finnish pulp and

	Mill	MetLow	MetMed	MetHigh
Market kraft pulp mill	Pulp1	1364	522	718
	Pulp2	1516	840	745
	Pulp3	1482	759	740
	Pulp4	1364	596	729
	Pulp5	1662	814	743
SC/LWC paper mill	MagzP1	2557	3425	900
	MagzP2	2005	2085	820
	MagzP3	1676	982	754
Integrated fine paper mill	FineP1	1785	1551	788
	FineP2	1676	964	752
	FineP3	1723	1401	779
Testliner mill	TestL1	1676	992	754
	TestL2	1676	699	737
	TestL3	1676	921	750
	TestL4	1676	880	747
Newsprint mill	NewsP1	1849	1706	797
	NewsP2	2027	2139	823

VI. Marginal methanol price (USD/metric ton$_{MeOH}$) for each case.

paper industry by the year 2035 [45]. However, totally carbon-neutral or carbon-negative production requires negative emissions, for example, in the form of BECCS. NETs are important for efficient emission reduction, especially in energy-intensive sectors like the pulp and paper industry where energy efficiency improvements offer only a minor solution.

Recently, NETs have mainly been set and/or discussed in Europe and in the United States. Financial and policy measures are essential to promoting carbon capture investments; also, tax policies are significant drivers of decarbonization. Although carbon capture technologies have primarily been targeted at reductions in fossil emissions, incorporation of biogenic sources as part of the mix can offer a more cost-effective way towards zero emissions. Carbon capture costs mostly depend on unit size, CO_2 concentration, and energy cost [46,14]. As unit size significantly affects the specific capture cost [46], large biogenic sources such as the recovery boilers at pulp and paper mills, could offer a competitive option for carbon capture, given that they are similarly subsidized as the fossil sources. Large biogenic sources can more cost effectively enable CO_2 reduction than smaller fossil ones. Economic feasibility would require one or more of the following: revenue from the products of CCU, support for the capital investment (e.g., in the form of a capital grant or loan guarantee), or emission taxes/negative emission credit. The emission trade schemes mentioned earlier offer at least a partial solution, given that they would consider negative emissions. In the United States, the 45Q tax credit first introduced in 2018 provides credits for stored or utilized CO_2 for power or industrial plants and facilities capturing CO_2 from air [47]. In the EU, the European Green Deal Investment Plan financially supports the Green Deal strategy including, for example, investment support for CCU projects via the Innovation Fund and the InvestEU program [48]. Renewable methanol competes with cheaper fossil methanol and is likely to need subsidies or legislative pressure to gain market. A step forward was recently taken in the EU when fuels based on CCU and low-carbon electricity were included in the renewed EU Directive on the promotion of the use of energy from renewable sources [6].

The results of this study indicate that the economic performance and the energy efficiency of the mills seem not to affect the feasibility of the studied processes. Therefore, it can be concluded that carbon capture and the subsequent processes are a new dimension and do not evidently correlate with the performance, technical age, or the measured efficiency of the mill. This makes it challenging to choose

	Mill	MetLow	MetHigh
Market kraft pulp mill	Pulp1	62	1029
	Pulp2	29	488
	Pulp3	26	438
	Pulp4	28	460
	Pulp5	16	272
SC/LWC paper mill	MagzP1	8	134
	MagzP2	6	108
	MagzP3	28	459
Integrated fine paper mill	FineP1	25	422
	FineP2	35	585
	FineP3	28	471
Testliner mill	TestL1	54	900
	TestL2	32	535
	TestL3	21	351
	TestL4	29	477
Newsprint mill	NewsP1	6	94
	NewsP2	6	92

VII. Annual methanol production (1000 metric tons$_{MeOH}$/year) in the studied cases.

the mill types where the new processes should be first promoted. A combination of solutions will be needed to combat climate change, as well as in the pulp and paper sector. The sector is diverse and requires process-specific solutions for decarbonization. The data on Nordic mills used in this study shows that fossil CO_2 emission intensity can be low and carbon capture enables negative emissions with relatively low efforts, especially in countries with vast biomass resources and where the products are mostly of virgin fiber. Recycled fiber processes have globally gained ground, but do not have similar potential for BECCS/BECCU as the kraft process due to different energy procurement. BECCS/BECCU can have a significant role in the pulp and paper sector, although it cannot act as a sole solution.

The Nordic pulp and paper units offer the possibility to apply BECCS/BECCU to become large point sources of CO_2 without additional land use or biomass harvesting. The pulp and paper industry has already targeted higher sustainability and fossil fuel-free operation by implementing new processes, as in Finland [17,49], for example. The sector is also actively looking for possibilities to be a part of the bioeconomy of the future, especially when demand for paper products change. Advanced technologies to produce wood-based products, such as substitutes for plastics or textile fibers, have been under research lately. The pulp industry has, however, shown little interest in synthetic fuel or specialty chemical production. Reasons for this can be the lack of incentives for carbon capture, especially biogenic carbon, and the relatively poor profitability of green fuels or products compared with fossil ones. The significance of advanced biobased products in the economics of the pulp and paper industry is of interest in the near future. The willingness of policymakers to create policy instruments to promote the development by, for example, supporting negative emissions will be a key role. A clear long-term policy framework is needed to encourage industrial operators to adapt new technologies. The development of emission trade systems in the large pulp producing countries is likely to affect the market prices of pulp and paper products; one of the important questions is the status of biobased CO_2 and its capture, storage, and reuse.

CONCLUSIONS

The pulp and paper sector is a significant user of energy biomass. It thus offers a significant potential for BECCS/BECCU application in existing mills without additional biomass harvesting. BECCS/BECCU integration can also act as one of the key measures in reducing CO_2 emissions in mills. Although the share of fossil fuel-based CO_2 emissions is low in many mills, the potential need to purchase emission allowances in the future will increase the production costs for pulp and paper. The low share of fossil CO_2 emissions enables zero or even negative CO_2 emissions with a relatively small carbon capture in many mills, especially market kraft pulp mills. Application of carbon capture is technically feasible in pulp and paper mills, but its economic feasibility requires a negative emissions compensation to cover the capture costs. Based on the results of this study and recent estimates on the capture costs, the minimum compensation for a kraft pulp mill is at least 75 USD/metric ton_{CO2}, depending on the mill details. The utilization of captured carbon for methanol production offers the potential to produce a sellable bioproduct, but requires low electricity prices, high negative emission compensation, or a methanol sale price significantly exceeding the current fossil methanol prices. The economic feasibility of the studied processes depends on the mill type and details but does not seem to correspond with the economic performance, technical age, or the measured energy efficiency of the mills. Carbon capture from pulp and paper mills followed by green methanol synthesis has a significant potential to answer to the future demand for biobased products in transportation and the chemical industry, but at the moment, the economic feasibility seems uncertain. Carbon capture or green fuel production can, however, be economical with an emission trade framework, including negative emission compensation and green fuel premium, depending also on electricity price and the emission profile of the mill. **TJ**

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding from the Academy of Finland for the project "Role of forest industry transformation in energy efficiency improvement and reducing CO_2 emissions," Grant Number 315019.

LITERATURE CITED

1. IEA, "Tracking Industry 2020," report, International Energy Agency, Paris, 2021. Available [Online] https://www.iea.org/reports/tracking-industry-2020 <17Aug2021>.
2. Vakkilainen, E., Kuparinen, K., and Heinimö, J., "Large industrial users of energy biomass," IEA Bioenergy Task 40: Sustainable International Bioenergy Trade, 12 September 2013. Available [Online] https://task40.ieabioenergy.com/wp-content/uploads/sites/6/2013/09/t40-large-industrial-biomass-users.pdf <17Aug2021>.
3. Jönsson, J. and Berntsson, T., *Energy* 44(1): 641(2012). https://doi.org/10.1016/j.energy.2012.05.028.
4. Kuparinen, K., Vakkilainen, E., and Tynjälä, T., *Mitig. Adapt. Strateg. Glob. Change* 24: 1213(2019). https://doi.org/10.1007/s11027-018-9833-9.
5. Onarheim, K., Santos, S., Kangas, P., et al., *Int. J. Greenhouse Gas Control* 66: 60(2017). https://doi.org/10.1016/j.ijggc.2017.09.010.
6. Lehtonen, J., Alakurtti, S., Arasto, A., et al., "The carbon reuse economy — Transforming CO_2 from a pollutant into a resource," VTT Technical Research Centre of Finland, Espoo, Finland, 2019.
7. European Commission, "In-depth analysis in support of the COM(2018) 773: A Clean Planet for all — A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy," European Commission, Brussels, 2018. Available [Online] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf <17Aug2021>.
8. European Commission, "The European Green Deal," COM(2019) 640 final, European Commission, Brussels, 2019.
9. Moya, J.A. and Pavel, C.C., "Energy efficiency and GHG emissions: Prospective scenarios for the pulp and paper industry," EUR 29280 EN, Publications Office of the European Union, Luxembourg, 2018.
10. Fridahl, M. and Lehtveer, M., *Energy Res. Soc. Sci.* 42: 155(2018). https://doi.org/10.1016/j.erss.2018.03.019.
11. UNFCCC, "Communication of long-term strategies," United Nations, 2021. Available [Online] https://unfccc.int/process/the-paris-agreement/long-term-strategies <17Aug2021>.
12. Larson, E., Greig, C., Jenkins, J., et al., "Net-Zero America: Potential pathways, infrastructure, and impacts," interim report, Princeton University, Princeton, NJ, USA, 2020.
13. CARB, "Cap-and-trade program," California Air Resources Board, Sacramento, 2020. Available [Online] https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program <17Aug2021>.
14. Kearns, D., Liu, H., and Consoli, C., "Technology readiness and costs of CCS," Global CCS Institute, Melbourne, Australia, 2021. Available [Online] https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf <17Aug2021>.
15. Kähkönen, S., Vakkilainen, E., and Laukkanen, T., *Energies* 12(19): 3689(2019). https://doi.org/10.3390/en12193689.
16. Kuparinen, K., Lipiäinen, S., Vakkilainen, E., et al., "Boundary conditions for economical implementation of BECCS in the Nordic pulp and paper industry," *2nd Int. Conf. Negative CO_2 Emissions*, Chalmers University of Technology, Gothenburg, Sweden, 2022 [accepted].
17. IRENA, "Bioenergy from Finnish forests: Sustainable, efficient and modern use of wood," International Renewable Energy Agency/VTT Technical Research Center of Finland/ Ministry of Economic Affairs and Employment of Finland, Abu Dhabi/Espoo/Helsinki, 2018.
18. "Statistics," Finish Forest Industries Federation, Helsinki, 2020.
19. "Publications of the emissions trading," Energy Authority of Finland, Helsinki, 2019. Available [Online] https://energiavirasto.fi/en/publications-of-the-emissions-trading <17Aug2021>.
20. European Commission Directorate General Climate Action, "Guidance on determining the allocation at installation level," Guidance Document n°2 on the harmonized free allocation methodology for the EU ETS post 2020, European Comission, Brussels, 2019. Available [Online] https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/p4_gd2_allocation_methodologies_en.pdf <17Aug2021>.
21. FAO, "FAOSTAT – Forestry production and trade," Food and Agriculture Organization of the United Nations, Rome, 2021. Availiable [Online] http://www.fao.org/faostat/en/#data/FO <17Aug2021>.
22. Stenqvist, C. and Åhman, M., *Climate Policy* 16(2): 125(2016). https://doi.org/10.1080/14693062.2014.979130.
23. Fleiter, T., Fehrenbach, D., Worrell, E., et al., *Energy* 40(1): 84(2012). https://doi.org/10.1016/j.energy.2012.02.025.

24. "Fuel classification 2020," Statistics Finland, Helsinki, 2020. Available [Online] https://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html <17Aug2021>.

25. Alakangas, E., Hurskainen, M., Laatikainen-Luntama, J., et al., "Properties of fuels used in Finland," VTT Technical Research Centre of Finland, Espoo, Finland, 2016.

26. Leeson, D., Mac Dowell, N., Shah, N., et al., *Int. J. Greenhouse Gas Control* 61: 71(2017). https://doi.org/10.1016/j.ijggc.2017.03.020.

27. IEAGHG, "Techno-economic evaluation of retrofitting CCS in a market pulp mill and an integrated pulp and board mill," IEA Greenhouse Gas R&D Programme, Cheltenham, UK, 2016.

28. Onarheim, K., Santos, S., Kangas, P., et al., *Int. J. Greenhouse Gas Control* 59: 58(2017). https://doi.org/10.1016/j.ijggc.2017.02.008.

29. Karjunen, H., Tynjälä, T., Hyppänen, T., *Appl. Energy* 205: 33(2017). https://doi.org/10.1016/j.apenergy.2017.07.111.

30. Vakkilainen, E. and Kivistö, A., "Forest industry energy consumption — trends and effects of modern mills," Lappeenranta University of Technology, Lappeenranta, Finland, 2014.

31. Fuss, S., Lamb, W., Callaghan, M., et al., *Environ. Res. Lett.* 13(6): 063002(2018).

32. Lehner, M., Tichler, R., Steinmüller, H., et al., *Power-to-Gas: Technology and Business Models*, Springer, Heidelberg, 2014. https://doi.org/10.1007/978-3-319-03995-4.

33. Koponen, J., "Energy efficient hydrogen production by water electrolysis," Ph.D. thesis, Lappeenranta-Lahti University of Technology (LUT), Lappeenranta. Finland, 2020.

ABOUT THIS PAPER

Cite this article as:
Kuparinen, K., Lipiäinen, Vakkilainen, E., *TAPPI J.* 20(8): 527(2021). https://doi.org/10.32964/TJ20.8.527

DOI: https://doi.org/10.32964/TJ20.8.527

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

34. Schmidt, O., Gambhir, A., Staffell, I., et al., *Int. J. Hydrogen Energy* 42(52): 30470(2017). https://doi.org/10.1016/j.ijhydene.2017.10.045.

35. Kuparinen, K., Vakkilainen, E., and Ryder, P., *Appita J.* 69(1): 81(2016).

36. Van-Dal, É.S. and Bouallou, C., *J. Cleaner Prod.* 57: 38(2013). https://doi.org/10.1016/j.jclepro.2013.06.008.

37. Hurskainen, M., "Economic feasibility of CO_2 utilization – Case pulp mill," *Final Seminar of the BIOCO$_2$ project*," VTT Technical Research Centre of Finland, Espoo, Finland, 2018.

38. Bos, M.J., Kersten, S.R.A., and Brilman, D.W.F., *Appl. Energy* 264: 114672(2020). https://doi.org/10.1016/j.apenergy.2020.114672.

ABOUT THE AUTHORS

We believe that carbon capture will soon be an essential part of industrial processes and that the pulp and paper industry needs knowledge about how to economically apply it and what kind of possibilities it provides. We have previously studied the technical possibilities for applying carbon capture and utilization or storage (CCUS) processes in the pulp and paper industry, and this study adds to the knowledge of its feasibility in different types of mills.

The pulp and paper industry is a diverse sector, and use of statistics as the basis for the study included uncertainties. We used several sources to make sure we have the correct and comparable data as the basis for this study.

We found that renewable hydrocarbons could, in some mills, soon be a profitable product. We also found that the feasibility of CCUS processes was not dependent on the mill type as much as was expected. It was interesting to note that whether the mill could be among the first ones in implementing CCUS is more dependent on mill-specific details than on the mill type or product portfolio.

We wish to offer mills new knowledge on CCUS implementation, as carbon capture is one of the important measures in emissions reduction. We believe mills will benefit from being on the front line in evaluating its possibilities.

We see three routes for further studies: deeper understanding of the specific requirements for CCUS implementation in varying types of mills; other CCU routes and their possibilities in the mills in addition to the methanol that was studied here; and a more detailed analysis on the effects of policy instruments in different types of mills.

Kuparinen

Lipiänen

Vakkilainen

Kuparinen is post-doctoral researcher, Lipiäinen is junior researcher, and Vakkilainen is professor in the Laboratory of Sustainable Energy Systems and LUT School of Energy Systems at Lappeenranta-Lahti University of Technology (LUT) in Lappeenranta, Finland. Email Kuparinen at katja.kuparinen@lut.fi.

39. MMSA, "Methanol price and supply/demand," Methanol Market Services Asia, Singapore, 2021. Available [Online] https://www.methanol.org/methanol-price-supply-demand/ <17Aug2021>.

40. "CO_2 European emission allowances," *Markets Insider*, 2020. Available [Online] https://markets.businessinsider.com/commodities/co2-european-emission-allowances <17Aug2021>.

41. Zero Emissions Platform, "The costs of CO_2 capture, transport and storage," European Technology Platform for Zero Emission Fossil Fuel Power Plants/European Commission, Brussels , 2011. Available [Online] https://zeroemissionsplatform.eu/wp-content/uploads/Overall-CO2-Costs-Report.pdf <17Aug2021>.

42. Market Observatory for Energy of the European Commission, "Quarterly report on European electricity markets," European Commission, Brussels, 2020. Available [Online] https://ec.europa.eu/energy/sites/ener/files/qr_electricity_q1_2020.pdf <17Aug2021>.

43. EIA, "Electricity," U.S. Energy Information Administration, Washington, DC, 2020.

44. Fastmarkets, "Pulp price volatility: Seven things you need to know." Available [Online], 2021. https://www.fastmarkets.com/article/3988710/pulp-price-volatility-seven-things-you-need-to-know <19Aug2021>.

45. Lipiäinen, S. and Vakkilainen, E., *Mitig. Adapt. Strateg. Glob. Chang.* 26(2): 9(2021). https://doi.org/10.1007/s11027-021-09946-5.

46. Garðarsdóttir, S., Normann, F., Skagestad, R., et al., *Int. J. Greenhouse Gas Control* 76: 111(2018). https://doi.org/10.1016/j.ijggc.2018.06.022.

47. Beck, L., "The US section 45Q tax credit for carbon oxide sequestration: An update," brief, Global CCS Institute, Melbourne, April 2020. Available [Online] https://www.globalccsinstitute.com/wp-content/uploads/2020/04/45Q_Brief_in_template_LLB.pdf <17Aug2021>.

48. European Commission, "Commission communication on the European Green Deal investment plan," European Commission, Brussels, 2020.

49. Metsä Group, "Metsä Group renewed its strategic sustainability objectives," press release, Metsä Group, Helsinki, 2019. Available [Online] https://news.cision.com/metsaliitto-osuuskunta/r/metsa-group-renewed-its-strategic-sustainability-objectives,c2753393 <17Aug2021>.