

Energy efficient alternatives to reduce the carbon emissions in the production of linerboard

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ABSTRACT

The variation in the prices of fossil fuels and the commitment to reduce GHG emissions have driven the US pulp and paper industry to adapt technologies to break the dependency on fossil sources. In this sense, improving energy efficiency is a vital strategy to decarbonize the sector. The present study evaluates the implementation of energy-efficiency alternates in key areas in the production of linerboard, including the concentration of black liquor, steam generation in recovery and auxiliary boilers, and the press and drying section in the paper machine. The technologies include: a) installing a high-efficiency recovery boiler and replacing natural gas boilers with electric boilers, b) graphene oxide (GO) nanofiltration membranes and mechanical vapor recompression (MVR) systems for black liquor concentration, c) Paper machine technologies including shoe press, a modified felt (nylon mesh) in the press section, and condebelt for drying. The technologies are evaluated based on detailed process simulations in WINGEMS, Life Cycle Assessment within the OpenLCA software, and financial models to determine the cost of avoided carbon. This parameter is the base to construct the carbon abatement cost curve, a methodology to categorize the alternative by its cost-effectiveness.

The analysis showed that the use of GO-nanofiltration membranes to pre-concentrate the black liquor and the installation of a condebelt in the drying section were the best alternatives with a 15% reduction in emissions scope 1,2, and 3. In addition, installing a high-efficiency recovery boiler provides an additional 10% carbon reduction. On the other hand, the financial analysis showed that the nylon felt in the press section, the installation of a shoe press, and the mechanical vapor recompression system for black liquor evaporation are alternatives with an important reduction in the operating cost, allowing a return on the investment. These technologies offer a maximum 8% reduction in carbon emissions, with a cost of avoided carbon (CAC) ranging between -\$67 to -\$19 per metric tonne CO₂-eq avoided, representing a saving to the mill. In contrast, the GO-nanofiltration membrane system and the recovery boiler study shows that the benefits of MVR, GO-nanofiltration membrane, electric boilers, and condebelt are enhanced in a scenario where the higher participation of renewable energies reduces carbon emissions in the US electric system. Therefore, the electrification of the pulp and paper industry under this scenario represents an opportunity to decarbonize the sector.

INTRODUCTION

The pulp and paper sector is an significant contributor to carbon emissions, being responsible for 2% of all emissions from industry in 2021 (about 190 Mt of CO₂).¹ As production is projected to increase by 2030, significant efforts must be made to break the dependency on fossil fuels and reduce energy demand. According to the International Energy Agency, the emission intensity of the sector has to decrease by 4% annually between 2021 and 2030 to achieve a zero CO₂ emissions scenario for the energy sector by 2050.¹

Among the different products offered by the pulp and paper industry, linerboard has a growing market by the demand for lightweight packaging material; the containerboard market size was over US \$160 billion in 2018, and the industry is expected to expand to US \$250 billion by 2025.² Linerboard is a key component in corrugated cardboard packaging,

is a biodegradable, renewable and recyclable product, making it a sustainable material.³ However, its sustainability depends on the energy efficiency of the process, the source of raw materials, and responsible forest management practices.

One of the key areas in the manufacturing process with a high energy demand is the paper machine drying section; about 20% of the total energy consumed in the process is used for paper drying.⁴ The implementation of technologies to reduce the water content from 50% to 35% of paper webs entering the drying section could save 80 trillion Btu annually in the United States.⁴ Other option to reduce the demand in the drying section, particularly in linerboard production, is the condebelt. This technology replace the drying section of a conventional paper machine, with a drying rate 5-15 times higher than conventional steam drying.⁵

Another section of high relevance in the process is the concentration of black liquor. Black liquor is the main source of energy in the kraft pulping process; this stream contains most of the pulping chemicals and the dissolved wood solids from the pulping process. The black liquor is concentrated to a high-solids content before being burned in the recovery boiler. This concentration takes place in a multiple effect evaporator with a high steam demand; about 7% of pulp and paper energy demand in U.S. kraft mills (164 trillion BTU per year) is used to black liquor concentration.⁶

Other critical area in the reduction of carbon emissions is the power plant. The steam production efficiency can be improved by introducing high power features (steam at high pressure and temperature) in the recovery boiler including higher black liquor dry solids, air preheating, feedwater preheating, heat recovery from vent gases, heat recovery from flue gases in a flue gas cooler, and higher steam parameters.⁷ High-efficiency recovery boilers can reduce the carbon emissions by providing additional steam and, therefore more power generation in the turbine,⁸ or by reducing the fossil fuel demand to cover the steam demand in the process. Another carbon reduction alternative in the power plant is the replacement of the natural gas boiler with high-efficiency electric boilers. A previous study has shown that electrifying boilers in various industrial sectors leads to an overall increase in GHG emissions based on the current national grid mix, but in future grid scenarios, where the percentage of coal and natural gas in the electric grid mix decrease by a higher participation of renewable energies, the overall GHG emissions would be reduced.⁹

In our previous study, the replacement of natural gas with biofuels in lime kiln operations and the use of biomass for steam and power generation were evaluated as alternatives to decarbonize the production of linerboard. The maximum reduction achieved for emission scope 1 and 2 with these alternatives was 93.1%. Increased reductions above 93.1% can be realized by improving the energy efficiency in the manufacturing process. In this regard, besides the increase in the use of bioenergy, reducing the steam demand in critical areas and improving the efficiency of steam generation are strategies to enhance carbon reductions. In the present study, various alternatives to reduce carbon emissions in a linerboard mill are evaluated, including technologies to improve energy efficiency in the steam generation operations, technologies to improve black liquor concentration, and technologies in the paper machine to improve dewatering and drying efficiencies.

It is worth mentioning that the present analysis takes into account the complex interactions between steam demand, fuel dependency and power production. Any improvement in the steam demand reduces the dependency on external fossil sources but, at the same time, reduces the capacity to generate electricity in the mill. This effect is addressed by simultaneously modeling the areas that compose the mill and estimating the reduction in the on-site emissions, the change in the demand for external fuels, and the changes in the power generation by reducing the steam flow in the system. The major conclusion is that it is important to evaluate technology changes not as isolated operations but holistically with respect to all mill operations to truly determine the overall mill carbon footprint improvements.

MATERIALS AND METHODS

Definition of the scenarios

The simulation model for the production of linerboard was described earlier and is briefly shown here. Figure 1 is the flowsheet for the process. Softwood logs are debarked, followed by chopping into wood chips; some external woodchips are also purchased for the pulping process. The wood chips are then cooked to remove lignin. The pulp is washed and sent to the paper machine, where the fibers are suspended in water, then the excess water is drained, forming a continuous sheet for further drying by suction, pressure, and heat. The liquor from the pulp washing is called

weak black liquor. This weak black liquor is concentrated in a multiple-effect evaporator and then burned in the recovery boiler to generate steam and convert the inorganic elements into a mixture of molten salts (primarily sodium carbonate and sulfide) called smelt. The smelt is sent to the causticization plant to recover the pulping chemicals. The waste wood from the wood yard and external waste biomass are burned in a hog fuel boiler, the heat demand is complemented by a natural gas boiler. The high-pressure steam from the boilers is expanded in a back-pressure and condensing turbine to generate electricity for the mill, part of the medium and low-pressure steam from the turbines is extracted to cover the heat demand in the process. Additional electricity from the grid is purchased to cover the mill's demand.

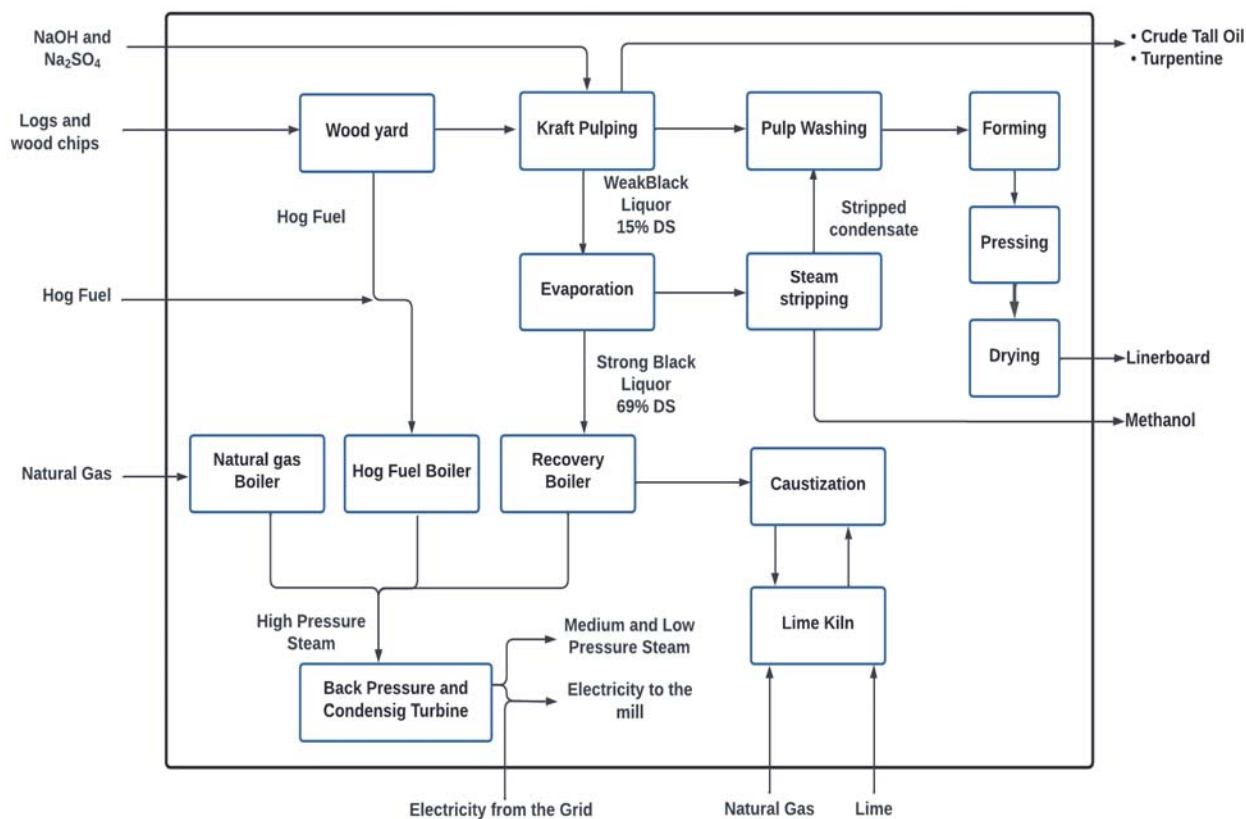


Figure 1. Simplified process flow diagram of a Linerboard mill.

The baseline simulation was modified to model the alternatives listed in Table 1. The capital investment, the changes in the operating parameters by integrating the alternatives, and the changes in the operating cost were determined according to the mass and energy balances from the simulation of each scenario and data reported in the literature. The scenarios and main assumptions are shown in Table 1. The linerboard production rate for the scenarios is the same; the carbon emissions were determined based on a Cradle-to-Gate LCA by implementing the IPCC 2013 GWP 100a method, this method expresses the greenhouse gases emissions in kilograms of CO₂ equivalent, over a time horizon of 100 years. The contribution of the upstream processes to the scenarios are based on the information reported by the Ecoinvent database.¹⁰

Table 1. Alternatives to improve the steam demand and steam generation in the production of Linerboard

TECHNOLOGIES FOR STEAM PRODUCTION		
Scenario	Base case	Alternative conditions
High-efficiency Recovery Boiler	Conditions in the recovery boiler. ^{11–13} -Steam condition: 850 F and 850 psi. -Flue gas temperature: 482 F (250°C). -Strong black liquor solids content: 69%.	Conditions in the recovery boiler ¹⁴ -Steam condition: 960 F and 1600 psi -Flue gas temperature: 356 F (180°C) -Strong black liquor solids content: 75% The condensing turbine and the multiple effect evaporator are rebuilt to operate under the above conditions
	Electric boilers	The natural gas boiler complements the steam produced by the recovery boiler and the hog fuel boiler to fulfill the steam demand in the process.
TECHNOLOGIES FOR BLACK LIQUOR CONCENTRATION		
Scenario	Base case	Alternative conditions
Graphene oxide (GO) nanofiltration membranes	The weak black liquor is concentrated in a multiple effect evaporator (MME) from 15% solids content to 69% using medium-pressure steam from the power plant that includes a recovery boiler, a hog fuel boiler, and a natural gas boiler. ^{11–13}	The membrane system pre-concentrate the weak black liquor from 15% to 30% solids content. The resulting liquor (permeate) is sent to the MME, and the filtrate is used to wash the pulp. The system reduces the steam demand but increases the electricity demand to operate the membranes at 60 MPa. ¹⁶
Mechanical vapor recompression		The weak black liquor is pre-concentrated from 15% to 25% by using the pressured water vapor from the black liquor evaporation. The system partially replaced the steam demand with electricity from the grid. ⁶
TECHNOLOGIES FOR PAPER MAKING		
Scenario	Base case	Alternative conditions

Shoe press	The web solids content leaving the press section in the paper machine is 50%.¹¹⁻¹³ The steam demand in the drying section is 1.43 kg steam/kg water evaporated.¹¹⁻¹³	The web solids are increased from 50 to 54%, with an increase in the electricity demand in the press section of 3.4.^{17,18} The steam demand in the drying section is 1.43 kg steam/kg water evaporated.¹¹⁻¹³
Felt modification (nylon mesh)		The web solids are increased from 50 to 61%, without affecting the electricity demand in the process.¹⁹ The steam demand in the drying section is 1.43 kg steam/kg water evaporated.¹¹⁻¹³
Condebelt		The technology saves an estimated 1.6 GJ/t paper in steam (around 15% of the steam demand) and 20 kWh/t paper in electricity.²⁰

Technologies for steam production

Two scenarios were evaluated for the steam generation: a) the replacement of the recovery boiler by a high-efficiency recovery boiler,¹⁴ and b) the replacement of the natural gas boiler by two electric boilers with a high efficiency (99%).¹⁵

High-efficiency recovery boiler

Replacing an old, inefficient recovery boiler with a newer, high-efficiency model is one way the pulp and paper industry can reduce carbon emissions. By upgrading to a high-efficiency recovery boiler, a pulp and paper mill can significantly reduce its carbon emissions by reducing the fossil fuels demand and electricity from the grid. This reduction is derived from an increase in the steam and the on-site power generation.¹⁴ In this alternative, the multiple-effect evaporation system and the condensing turbine are refurbished, given that the recovery boiler operates at higher black liquor solids content, and the steam generation increases.

Electric boilers

Electric boilers use electricity as energy source rather than direct fossil or biomass fuel combustion. There are a number of advantages to using electric boilers for steam generation in the pulp and paper industry, such as lower energy losses compared to combustion processes, zero on-site emissions, and operations that are easily adjusted to meet changing steam demand, and lower maintenance. However, electric boilers can be more expensive to operate than fossil fuel-fired boilers, particularly if electricity prices are high.¹⁵ In this scenario, the natural gas boiler is replaced by two high efficiency (99%) electric boilers,¹⁵ avoiding on-site fossil emissions but increasing the indirect emissions from the electricity demanded (Scope 2).

This scenario is included given that the US electric power sector has shown a 15% reduction in CO₂-eq emissions from 2007 to 2019 and are expected to continue to improve.²¹ In this regard, a sensitivity analysis is included to evaluate the alternatives considering the carbon emissions projected for the US electricity generation system under two scenarios, i) High cost for renewable energies: no cost reductions in renewable technologies, and ii) Low cost for renewable energies: renewables achieve 40% lower overnight capital costs by 2050.^{22,23}

Technologies for black liquor concentration

Black liquor concentration is one of the unit operations with the highest steam demand in the process, about 7% of pulp and paper energy demand is used to remove water from black liquor in US kraft mills.⁶ Two technologies are evaluated to reduce the steam demand in this area: Graphene oxide (GO) nanofiltration membranes and mechanical vapor recompression (MVR). These two technologies are implemented as a previous stage in the multiple effect evaporator to pre-concentrate the liquor to a 30% and 25% solids content, respectively.^{6,24}

GO nanofiltration membranes

The GO nanofiltration membranes system concentrates the weak black liquor from 15% to 30% dissolved solids; this significantly reduces the evaporator energy load and produces process-quality water that can be used to wash the pulp after pulping.¹⁶ However, the system operates at high pressure (60 MPa),¹⁶ increasing the electricity demand. In addition, the on-site electricity generation drops by the reduction in the steam flow in the turbines, increasing the emissions Scope 2. In addition, the membranes have a partial rejection towards dissolved inorganics, which affects the chemical demand. The mass and energy balance performed in the simulation addresses these combined effects in the electricity and chemical balance. Two scenarios were considered for this alternative, a system with four membranes (scenario Membrane 1) and a system with five membranes (scenario Membrane 2).

Mechanical vapor recompression

The mechanical vapor recompression system (MVR) reduces the steam demand by using the recompressed water vapor from the black liquor evaporation as a heat source. In this scenario, an additional external evaporation body is installed, the steam from this body is recompressed in a low-speed centrifugal fan, and the mechanically heated vapor is used as a heating medium in the same evaporator body.⁶ The system uses electricity rather than thermal energy (steam) to pre-concentrate the weak black liquor from 15% to 25%.⁶ Similar to the membrane system, for the MVR

the on-site electricity capacity drops by the reduction in the turbine's steam flow, affecting the emissions from Scope 2.

Paper machine technologies

Press section

The wet-press section plays a critical role because an essential fraction of the steam demand comes from the evaporation of water from the paper; the wet-press section is, therefore, the last chance to remove the water before evaporative drying.¹⁷ It is estimated that 3 to 8% of dryer steam consumption can be saved by improving the solids content of the web formed after the press section.¹⁸ Two alternatives are included for this section, the first is the adaptation of a shoe press, and the second is the introduction of a nylon mesh into the press felt.

A shoe press presses the paper web between a pair of rollers, with one roller coated in a flexible "shoe." The shoe press improves the mechanical dewatering by extending the dwell time in the nip, increasing 4 to 7 % points of dryness;¹⁷ this reduces the water to be evaporated in the drying section but with a 3 to 5 % increase in the electricity demand compared to a conventional press.¹⁸

On the other hand, incorporating a nylon mesh into the felt significantly reduces rewet by rupturing the liquid channels between felt and web. The nylon mesh is embedded into the surface of the continuous press felt and travels as an integral part of the moving press felt. This technique has been shown on a laboratory scale to increase the press solids from 48% to 61% on 120 g/m² southern bleached softwood kraft pulp handsheets.¹⁹

Drying section

The drying section is one of the most energy-demanding areas; 50% to 60% of the heat energy is consumed in the dryers.²⁵ Condebelt drying is a technology that saves an estimated 1.6 GJ/t paper in steam (around 15% of the steam demand) and 20 kWh/t paper in electricity;²⁰ and it is suitable for the production of linerboard.²⁵ In a condebelt dryer, the paper web is passed between a pair of flexible steel belts. The system is heated from one side using steam and cooled on the other with water. The condensate is collected in the bottom-cooled side by a pair of fabrics. Besides the energy savings, some properties are improved, such as strength (by 20 to 60 percent), surface smoothness, dimensional stability, and resistance against humidity.²⁰

Marginal Abatement Cost Curves

The alternatives were categorized by developing a Marginal Abatement Cost Curve (MACC). This curve is built based on the Cost of Avoided Carbon (CAC) in US \$/ton of CO₂-eq. and the CO₂-eq reduction achieved by implementing each technology for ten years. The MACC was built considering emissions Scopes 1 and 2, and the total emissions associated with the entire system (emissions Scopes 1, 2, and 3). The cost of each technology is determined as the NPV in an 11-year lifetime, out of which the first year is for construction, with a 15% rate of return. In addition, the NPV and the CAC of each alternative were estimated considering two carbon-offset prices, \$11/ metric tonne by 2030 and \$47/ metric tonne by 2050; these values are prices projected for technologies that avoid carbon emissions.²⁶

RESULTS AND DISCUSSION

Carbon reductions

Figure 2 shows the total carbon emissions by Scope 1, 2, and 3. All the scenarios represent a reduction in carbon emissions, except for the electric boilers. The membrane system to pre-concentrate the liquor and the condebelt in the paper machine had a maximum reduction of 14.7%, while the rest of the alternatives were below 10% reduction, the lowest being the shoe press, with 4.8%.

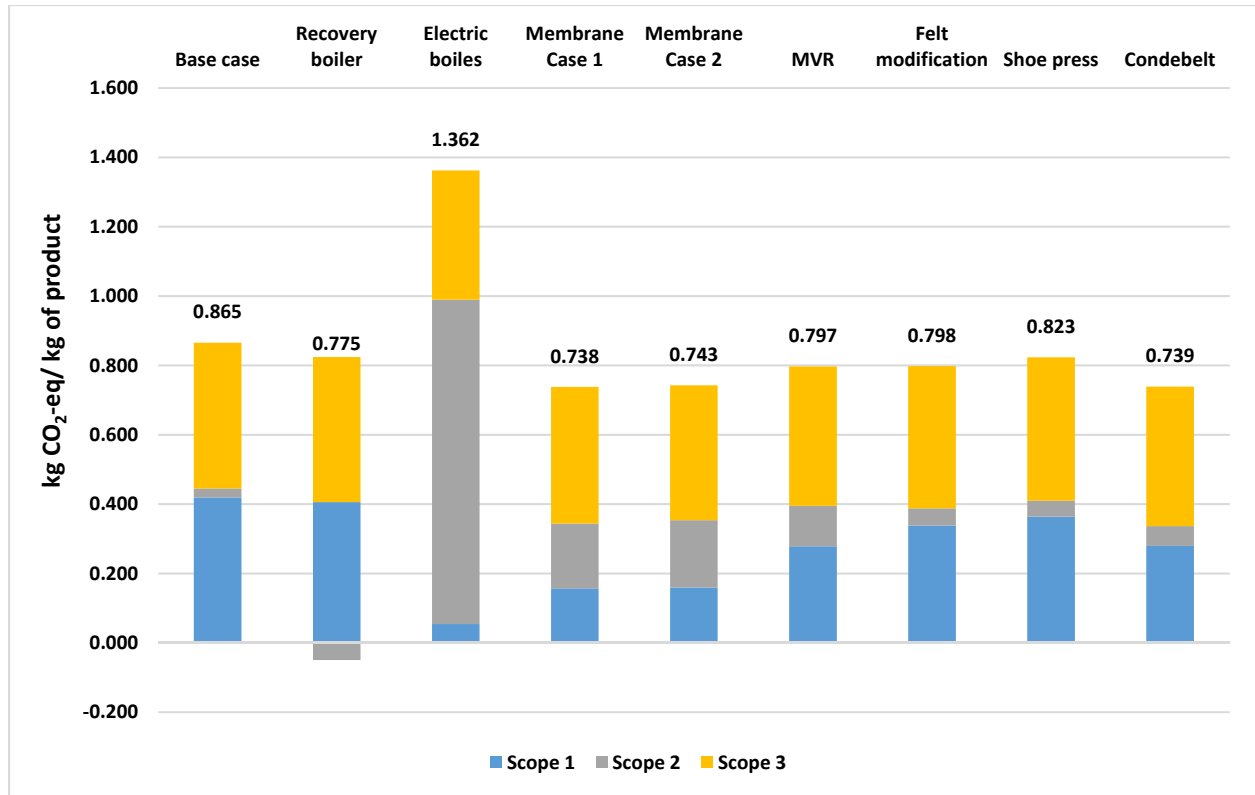


Figure 2. Emissions scope 1,2 and 3 for different technologies to improve the steam generation/demand in the production of linerboard

The hotspot analysis in Figure 3 shows the detailed change in the carbon emissions by area for each alternative. The percentage is calculated as follows:

$$\frac{(CO_2eq_{ij} - CO_2eq_{i,bc})}{Total\ CO_2eq_{bc}} * 100\%$$

Where i corresponds to the area, j to the scenario, and bc to the base case.

According to the hotspot analysis, implementing the high-efficiency recovery boiler reduces the carbon emissions by 10.5%. The new recovery boiler improves the steam generation (flow and energy content) from the black liquor combustion, and more steam is available for the refurbished condensing turbine. The electricity capacity is therefore increased to a level where the mill has surplus electricity sold to the grid. This surplus electricity represents an 8,7% reduction compared to the base case. At the same time, this improvement drops the natural gas demand for heat and power generation and, therefore, the on-site fossil emissions; the avoided natural gas represents a total 1.6% reduction.

In the electric boilers scenario, the emissions from the natural gas boiler are completely avoided; the only on-site fossil emissions come from the limekiln (Figure 2). However, the avoided emissions are countered by the electricity demanded to operate the boilers, increasing the net emissions by 57.2%. Still, it is expected that the US electric system will incorporate renewable energies, reducing the carbon emissions associated with the electricity demanded by the mill; this is discussed later.

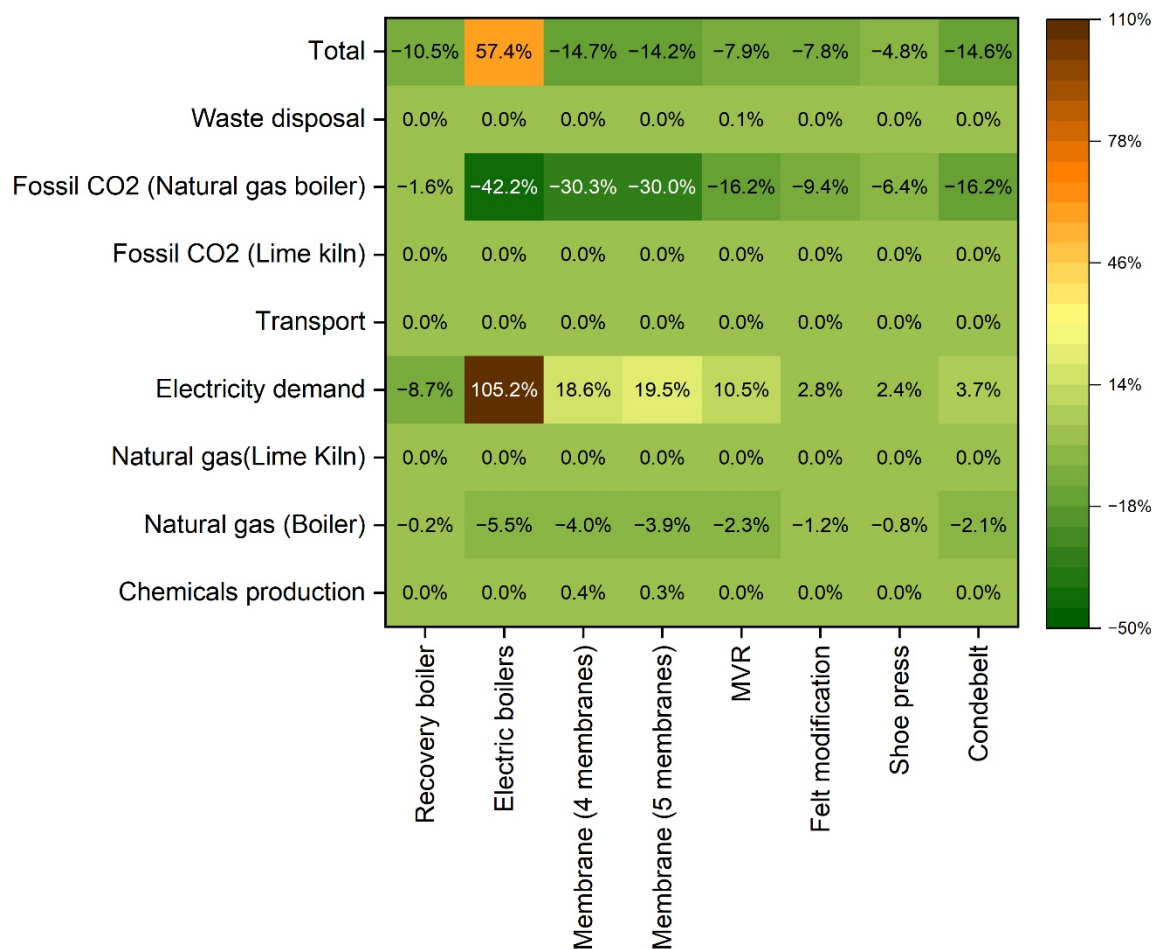


Figure 3. Hotspot analysis for carbon emissions of different technologies to improve the steam generation/demand in the production of linerboard

Regarding the graphene oxide membranes, the system offers savings in the steam demand to pre-concentrate the weak liquor from 15 to 30% solids. These savings represent a 30% reduction in carbon emissions by avoiding the combustion of natural gas in the boiler. However, the reductions are countered by the electricity required to pump the liquor through the membrane system, by the loss of pulping chemicals derived from the membrane's partial selectivity to inorganics, and by the drop in the on-site electricity from a lower steam flow in the turbines. In addition, increasing the number of membranes from four to five does not improve carbon emissions. The chemical recovery is enhanced by adding a fifth membrane, but the electricity demand increases, offsetting the chemical recovery's benefits in carbon emissions. The net carbon reduction for a 4-membrane system is 14.7%, while the 5-membrane system is 14.2%. Similarly to the membrane system, the MVR reduces the steam demand to concentrate the white liquor; these savings represent an 18.5% reduction in carbon emissions by avoiding the combustion of natural gas in the boiler. However, the savings are countered by the electricity demand in the fan that compresses the water vapor, and the reduction in the on-site electricity generation, resulting in a net 8% carbon reduction.

Regarding the alternatives implemented in the paper machine, the nylon felt and shoe press increase the web solids from 50% to 61% and 54%, respectively. This improvement in the web solids reduces the steam demand in the drying section and, therefore, the natural gas demand in the boiler. At the same time, the on-site electricity is reduced by the drop in the steam demand, increasing the emissions Scope 2. As a result, the net carbon reductions for the nylon felt and shoe press are 8 and 5 %, respectively.

In the case of the condebelt, this alternative offers higher savings in the steam demand compared to the nylon felt and the shoe press, however, the power drop in the turbine is countered by the electricity savings, giving a net reduction of 14.6%.

Marginal Abatement Cost Curves

The alternatives were categorized by developing a Marginal Abatement Cost Curve (MACC), the cost of the avoided carbon (CAC) was determined based on the NPV and the carbon reductions for 10 years. The MACC was built considering emissions Scope 1 and 2, and the total emissions associated with the entire system (scope 1, 2 and 3).

Direct cost structure

Figure 4 shows the direct cost structure for the scenarios under study. All the alternatives represent a saving in the operating cost except for the membrane system. The savings on natural gas in the alternatives implemented in the paper machine (shoe press, condebelt, and nylon) and the MVR were significantly higher than the cost from the additional electricity demanded by the alternatives.

Regarding the membrane system, the savings in natural gas are higher than the rest of the alternatives. However, the membranes have to be replaced annually, which implies a high operating cost for the mill. The area required to treat the black liquor is 176,400 and 240,580 m² for the 4 and 5-membrane system, respectively, with a membrane cost of \$200/m². Finally, the high-efficiency recovery boiler offers savings in the natural gas demand and a profit from the electricity sold to the grid.

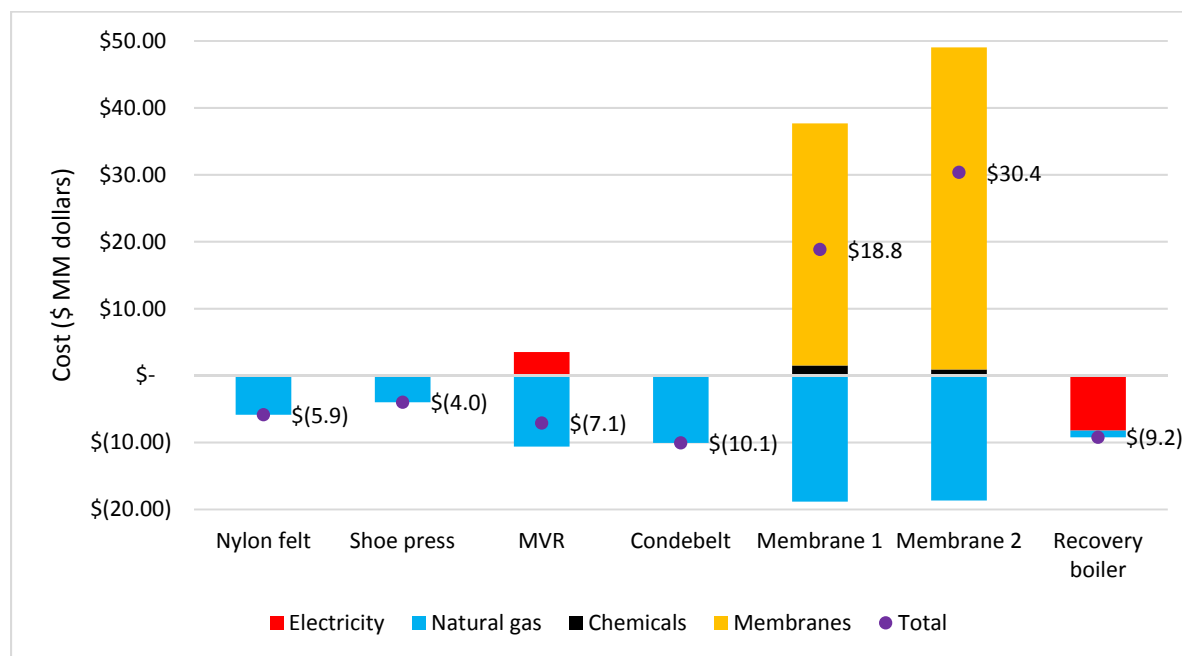


Figure 4. Annual direct operating cost structure of different technologies to improve the steam generation/demand in the production of linerboard

MACC-Emissions Scope 1 and 2

Figure 5a shows the MACC considering emissions Scope 1 and 2. The nylon felt, shoe press, and MVR have a CAC negative; this indicates that implementing the technologies represents an income for the mill. In these alternatives, the operational cost savings allow for the capital investment's recovery and a positive NPV for the ten years in operation. These three alternatives have the lowest capital investment, with savings in the operating cost between 4 to 7 million dollars.

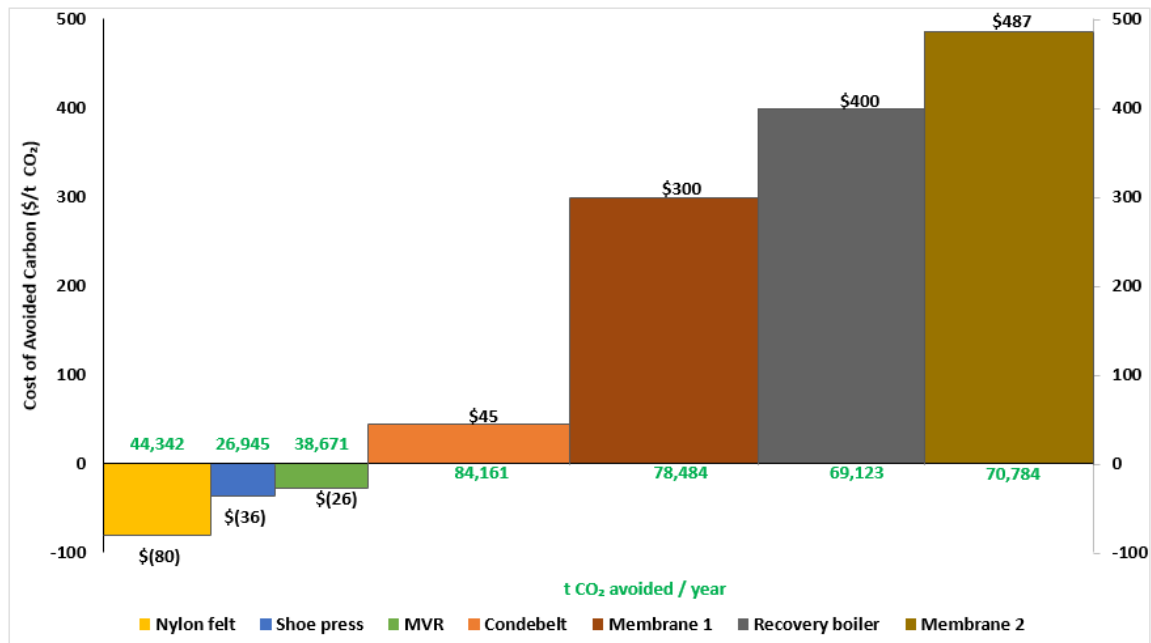
Regarding the condebelt, this alternative offers savings in the operating cost and carbon reductions higher than the other alternatives implemented in the paper machine (shoe press and nylon felt); however, the capital investment makes this alternative less cost-effective with a CAC of \$45/ metric tonne of CO₂-eq avoided.

In the case of the four-membrane system, this alternative has the maximum carbon reduction (bar width in Figure 5a), but with high operating cost by the annual replacement of the membranes; this, along with the capital investment, implies a CAC of \$300/ metric tonne of CO₂-eq avoided. The implementation of an additional membrane increases the indirect emissions (Scope 2), and the operating cost (additional area), increasing the CAC to \$487 /ton of CO₂-eq avoided. Finally, the high-efficiency recovery boiler makes the system self-sufficient in terms of electricity and offers a profit from the surplus electricity, but requires a high capital investment, resulting in a CAC of \$487/ton of CO₂-eq avoided.

MACC-Emissions Scope 1, 2 and 3

In regard to the MAC considering emissions scope 1, 2, and 3 (Figure 5b); the CAC is reduced. In this case, the total avoided emissions are higher by including the avoided emissions from the natural gas production and transport to the mill. This change in the CAC is more significant for the membrane alternatives, given the high savings in natural gas achieved (Figure 5).

a)



b)

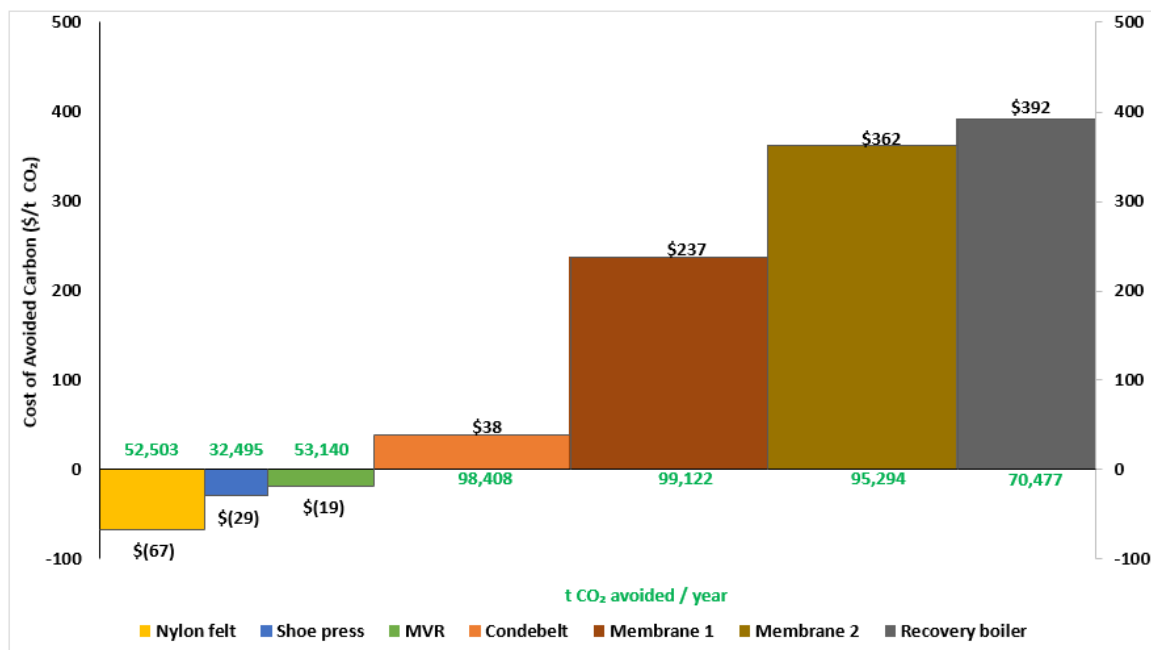


Figure 5. Marginal abatement cost curve for technologies to improve the steam generation/demand in the production of linerboard. The production rate for the mill is 2,177 tons per day a) Emissions including Scope 1 and 2, b) Emissions including Scope 1, 2 and 3

The CAC was also determined assuming a revenue from the avoided CO₂-eq emissions, considering emissions scope 1 and 2 only. Two prices are considered for the avoided emissions: \$11 per ton of CO₂-eq avoided, a price expected

by 2030 for technologies that prevent the emission of CO₂, and \$47 per ton of CO₂-eq avoided, the predicted value by 2050.²⁶ The NPV and the CAC for each offset price are shown in Table 2.

The CAC improves by assuming a profit from the carbon avoided; for instance, for the nylon felt scenario, the CAC changed from a saving of \$80 to \$108 / ton CO₂-eq, assuming a price of \$47/ ton CO₂-eq avoided. However, for the condebelt, the membrane system, and the high-efficiency recovery boiler, the revenue from the carbon avoided is not enough to counter the changes in the operating cost and the capital investment, resulting in a CAC positive, even for an offset price of \$47/ ton CO₂-eq avoided. For these alternatives, the minimum carbon price to prevent a cost for the mill, which means an NPV equal to zero, ranges from \$75/ ton CO₂-eq avoided for the condebelt technology to a maximum of 809/ ton CO₂-eq avoided for the 5-membrane system (last column in Table 2).

Table 2. Capital cost, Net Present Value, and Carbon Avoided Carbon for alternatives to reduce GWP in the production of linerboard. The NPV and the CAC were estimated assuming three prices for the carbon offsets: \$0, \$11, and \$47 dollars for ton of CO₂-eq, considering emissions scope 1 and 2²⁶

Scenario	ton CO ₂ -eq avoided /year	Capital Investment (Millions)	Maintenance capital (millions/year)	Operating cost (Millions/year)	Maintenance & Repair (Millions/year)	NPV (Millions)			CAC (dollars / t CO ₂ -eq avoided)			Minimum offset price for a NPV = 0 (\$/ ton CO ₂ -eq avoided)
						\$0/ t CO ₂ -eq avoided	\$11/ t CO ₂ -eq avoided	\$47/ t CO ₂ -eq avoided	Offset price = \$0/ ton CO ₂ -eq avoided	Offset price = \$11/ ton CO ₂ -eq avoided	Offset price = \$47/ ton CO ₂ -eq avoided	
Nylon felt	44,342	\$0	\$0	(\$5.86)	\$0	\$35.26	\$38.19	\$47.80	(\$80)	(\$86)	(\$108)	-
Shoe press	26,945	\$11.15	\$0.11	(\$3.99)	\$0.22	\$9.58	\$11.36	\$17.20	(\$36)	(\$42)	(\$64)	-
MVR	38,671	\$25.26	\$0.25	(\$7.11)	\$0.51	\$10.12	\$12.68	\$21.06	(\$26)	(\$33)	(\$54)	-
Condebelt	84,161	\$76.10	\$0.76	(\$10.06)	\$1.52	(\$37.86)	(\$32.29)	(\$14.06)	\$45	\$38	\$17	\$75
4-Membranes	78,484	\$122.23	\$1.22	\$18.83	\$2.45	(\$235.20)	(\$230.01)	(\$213.00)	\$300	\$293	\$271	\$498
5-Membranes	70,784	\$162.45	\$1.63	\$30.36	\$3.25	(\$344.65)	(\$339.96)	(\$324.62)	\$487	\$480	\$459	\$809
Recovery boiler	69,123	\$256.49	\$2.57	(\$9.22)	\$5.13	(\$276.16)	(\$271.59)	(\$256.61)	\$400	\$393	\$371	\$664

Sensitivity Analysis for the Cost of Avoided Carbon

Sensitivity analysis for the cost

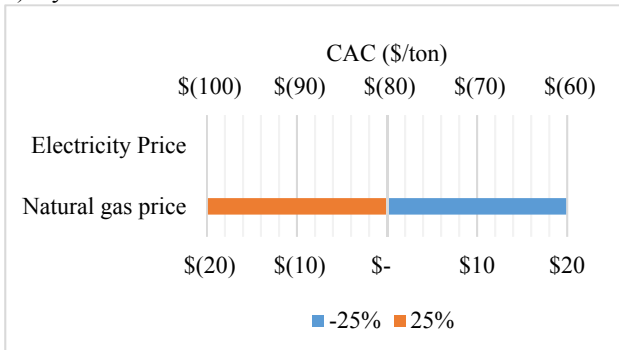
A sensitivity analysis was performed to determine the variables that affect the CAC. The CAC was determined by varying $\pm 25\%$ the costs of the electricity, natural gas, chemicals, and the capital investment without including any revenue from the carbon offset (Figure 6).

Regarding the alternatives to improve the energy efficiency in the paper machine, the primary variable for the nylon felt, and the shoe press is the natural gas price, with a variation of $\pm 25\%$ and $\pm 63\%$ in the CAC, respectively. On the other hand, the CAC for the condebelt varies $\pm 65\%$ with the capital investment and $\pm 40\%$ with the natural gas price. This alternative has a higher capital investment compared to the nylon felt, and the shoe press

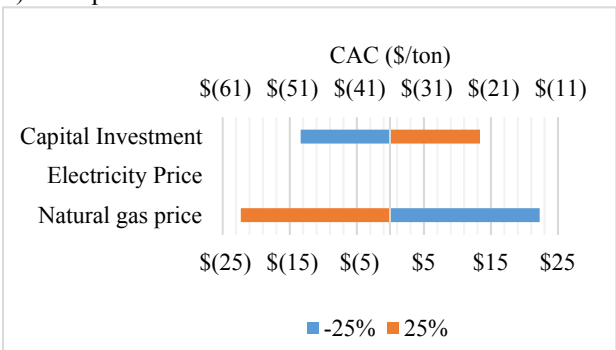
Concerning the technologies to concentrate the black liquor, the MVR has a CAC variation of $\pm 158\%$ with the natural gas price by the high savings achieved in the natural gas boiler, $\pm 81\%$ with the capital investment, and $\pm 52\%$ with the electricity. On the other hand, for the membrane system, the most relevant variable is the cost of the membranes. The variation is $\pm 19\%$ for the 4-membrane system and $\pm 17.5\%$ for the 5-membrane system, which is higher compared to the CAC variation with the total capital investment ($\pm 17\%$ and $\pm 15\%$), respectively. This shows that the membrane cost has to be reduced to make the system more cost-effective.

In the case of the high-efficiency recovery boiler, the capital investment is the most relevant variable in the CAC. This alternative has the highest capital investment but with limited revenue from the electricity surplus; for instance, the revenue from the electricity surplus is comparable to the natural gas savings achieved in the MVR and condebelt technology, technologies with lower reductions in the carbon emissions.

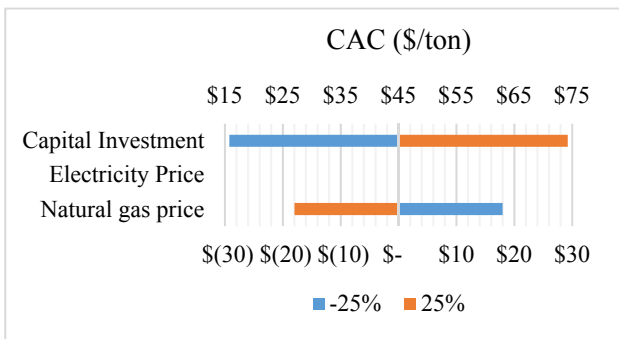
a) Nylon felt



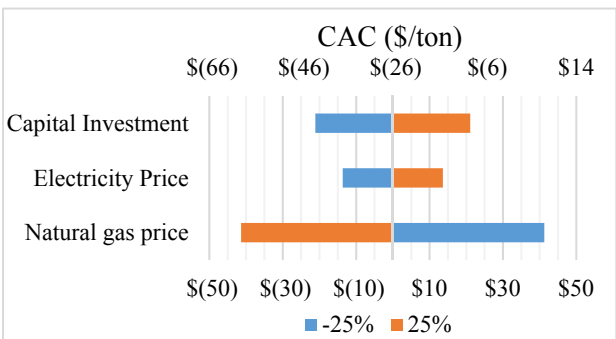
b) Shoe press



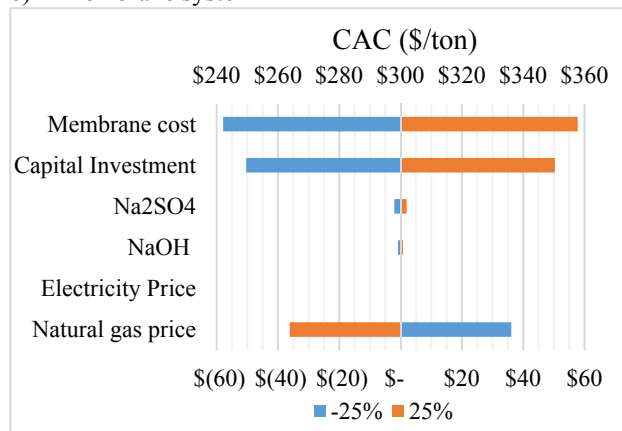
c) Condebelt



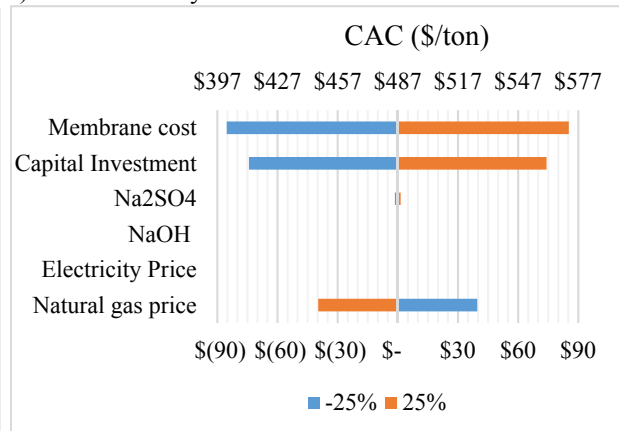
d) MVR



e) 4-Membrane system



f) 5-Membrane system



g) High efficiency recovery boiler

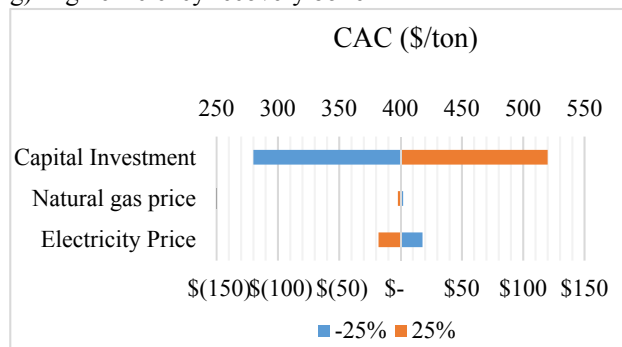


Figure 6. Sensitivity analysis for the Cost of Carbon Avoided (Scope 1 & 2). Change in the variables is +/- 25% of the value assumed for each scenario

Sensitivity analysis for the carbon emissions from the electricity demanded

A sensitivity analysis was developed using the emissions factors reported by the US Energy Information Administration for two scenarios that assume the introduction of renewable energies in the electric system under two conditions: i) High cost for renewable energies: no cost reductions in renewable technologies, and ii) Low cost for renewable energies: renewables achieve 40% lower overnight capital costs by 2050.^{22,23} The factors change across the time, for instance the emission factor in 2021 for both scenarios is 0.392 kg CO₂/kWh, while by 2050, the factors are 0.263 and 0.178 kg CO₂/kWh for the high and low cost for renewable energies, respectively.

Figure 7 shows the carbon emissions for each alternative assuming the electricity emission factor reported for the high-cost renewable energy scenario in a ten years frame. Under these conditions, the membrane system has the lowest carbon emissions, followed by the condebelt and the MVR. For the electric boilers scenario, the carbon emissions are reduced considerably from an initial value of 0.783 to 0.712 kg CO₂-eq /kg product. Given these variations in the carbon emissions along the time, the CAC was determined considering the total carbon reduction for each alternative for the ten years time frame, assuming the same NPV described previously. The results are included in Table 3.

Under these conditions, the carbon credits from the electricity sold to the grid decreases, which reduces the CAC for the high-efficiency recovery boiler. In contrast, for the electric boilers, instead of having an increase in the carbon emissions, the alternative offers a reduction by the lower impact of electricity imported to the system. For the rest of the alternatives, the effect is similar; the improvement in the electric system reduces the emissions from the electricity demand, reducing the CAC. The sensitivity analysis shows that the industry also has an opportunity to improve the carbon emissions by replacing the heat (steam) demand with electric energy, supported by the fact that the electric system in the US tent to reduce carbon emission by increasing the share of renewable energies.

43 Table 3. CAC for different energy efficiency alternatives assuming different carbon emission factors for the electricity
 44 demand

Alternative	Total carbon saved 2023-2033 (kg CO ₂ -eq)			CAC emissions scope 1,2 and 3 (\$/ton CO ₂ -eq)		
	Ecoinvent	High renewables cost	Low renewable cost	Ecoinvent	High renewables cost	Low renewable cost
Recovery Boiler	7.05x10 ⁵	3.393x10 ⁵	3.245x10 ⁵	\$392	\$814	\$851
Electric boilers	-3.86x10 ⁶	1.032x10 ⁶	1.211x10 ⁶	-	\$383	\$327
4-Membranes	9.91x10 ⁵	2.027x10 ⁶	2.059x10 ⁶	\$237	\$116	\$114
5-Membrane	9.53x10 ⁵	2.028x10 ⁶	2.061x10 ⁶	\$362	\$170	\$167
MVR	5.31x10 ⁵	1.114x10 ⁶	1.132x10 ⁶	\$(19)	\$(9)	\$(9)
Nylon felt	5.25x10 ⁵	7.201x10 ⁵	7.250x10 ⁵	\$(67)	\$(49)	\$(49)
Shoe press	3.25x10 ⁵	4.787x10 ⁵	4.828x10 ⁵	\$(29)	\$(20)	\$(20)
Condebelt	9.84x10 ⁵	1.267x10 ⁶	1.274x10 ⁶	\$38	\$30	\$30

45

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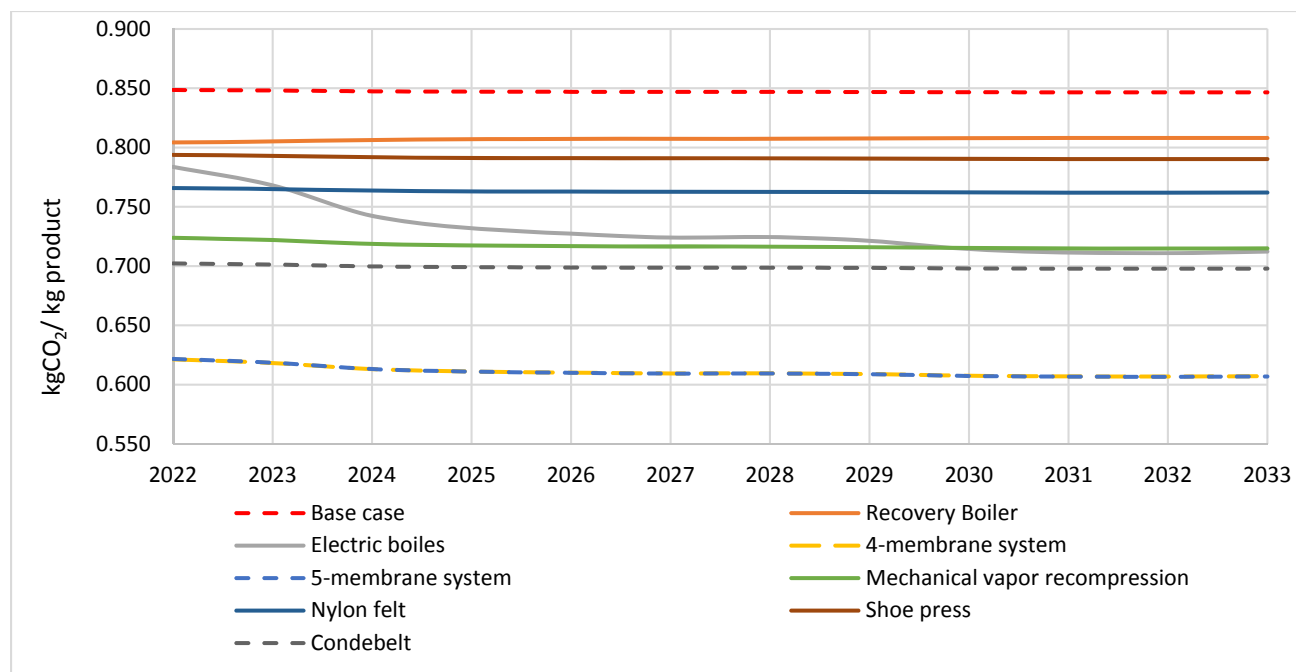


Figure 7. Carbon reductions for Linerboard production under a scenario with higher participation of renewable energies in the power generation system. Scenario: High cost for renewable energies

CONCLUSIONS

Implementing technologies to improve the production and use of steam are vital strategies to decarbonize the pulp and paper industry. In linerboard production, the reduction in the steam demand in key areas such as black liquor concentration and the drying section represents significant reductions in the total carbon emissions. The use of GO nanofiltration membranes to pre-concentrate the black liquor or the installation of a condebelt in the drying section reduces total carbon emissions by almost 15%. Moreover, improving the steam generation in the recovery boiler provides an additional 10% carbon reduction by increasing the steam and power generation.

On the other hand, the decision about what technology is more convenient has to be supported not only by the potential carbon reduction but also by the cost-effectiveness of the alternatives. In this regard, constructing the Marginal Abatement Cost Curve is a useful tool to determine the alternatives that offer not only potential savings in carbon emissions but also in cost. For instance, the use of a nylon felt in the press section, the installation of a shoe press, and the black liquor pre-concentration by a mechanical vapor recompression system represent an important reduction in the operating cost, allowing a return on the investment. These technologies offer a maximum reduction of 8%; but with a cost of avoided carbon (CAC) ranging between -67 to -19 dollars per ton, representing a saving to the mill. In contrast, a membrane system to concentrate the black liquor offers a 15% reduction in the carbon emission but under a CAC of \$237 to \$362 per ton of CO₂-eq avoided.

In addition, the industry also has the opportunity to improve the CAC by trading the carbon reduction in the market at a price of \$11 per ton of CO₂-eq avoided by 2030 and \$47 per ton of CO₂-eq by 2050. However, for alternatives with a high capital investment, such as condebelt, high-efficiency recovery boiler, and the black liquor membrane system, the price has to be above \$47/ton of CO₂-eq to recover the investment and avoid additional costs to the mill.

Finally, the electrification of the pulp and paper industry represents an opportunity to decarbonize the sector by reducing the on-site fossil emissions for steam generation. The carbon emissions in the US electric system are expected to be reduced by the higher participation of renewable energies in the generation; this fact enhances the benefits of

technologies such as MVR, the black liquor membrane system, electric boilers, and condebelt, where the heat demand is replaced by electricity.

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