Understanding the Energy and Emission Implications of New Technologies in a Kraft Mill: Insights from a CADSIM Plus Simulation Model

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ABSTRACT

Kraft mills play a vital role in the energy transition because they have significant potential to reduce their own energy utilization and produce energy/products to decarbonize other sectors. Through biomass combustion and potential biogenic carbon emissions capture, these mills can contribute to offsetting emissions from other sectors. This research investigates the departmental and cross-departmental implications of technology upgrades on energy, steam, emissions, water, chemicals, and economics using a CADSIM Plus simulation model. The model provides a comprehensive analysis of mass and energy balances, offering valuable insights into the benefits and limitations of each technology. The model facilitates scenario analysis and comparisons of process configurations, enabling data-driven decision-making for sustainable and competitive operations. Six high-impact technologies, including additional evaporator effects, weak black liquor membrane concentration, belt displacement washer for brownstock washing, oxygen delignification, and improvements to the pulp machine shoe press and vacuum pumps, are evaluated. Individual technologies resulted in energy savings of 1.2% to 5.4%, biomass consumption reductions of 8.6% to 31.6%, and total emissions reductions of 1.6% to 5.9%. Strategic decision-making must consider existing mill limitations, future technology implementation, and potential production increases. Future research will explore product diversification, biorefineries, and pathways to achieve carbon-negative operations, aiming to reduce emissions and secure a competitive future for Kraft mills.

INTRODUCTION

In today's necessity to decarbonize the Canadian economy, industry ought to accelerate towards renewable and sustainable fuels. Considering this challenge, pulp and paper mills can play an important role for GHG reductions for Canada as they rely heavily on biomass combustion and produce primarily biogenic carbon emissions. In 2022, the Canadian pulp and paper industry consumed 364PJ (79% bioenergy, 21% fossil) of fuels, excluding power and steam purchases and produced 30MtCO_2e (86% biogenic, 14% fossil) of direct emissions [1]. If these mills can become carbon negative by capturing part or all of their biogenic emissions, they can offset the emissions of more fossil fuel dependent industries or other sectors such as agriculture and transportation.

The objective of this work is to investigate the energy, steam, emission, water, chemical, and economic implications of pursuing several avenues that Kraft mills can undertake to be more sustainable and competitive in the future. These avenues include various technology upgrades, product diversification, fuel switching, and carbon capture as illustrated below in Figure 1 and are interconnected with one another (ex: a pulping improvement may allow for different pulp grades to be produced). Kraft mills in the future will need optimized operations, efficient resource management, diversified products, and highly efficient technology to maintain profitability, while also being committed to reducing emissions and environmental impacts.

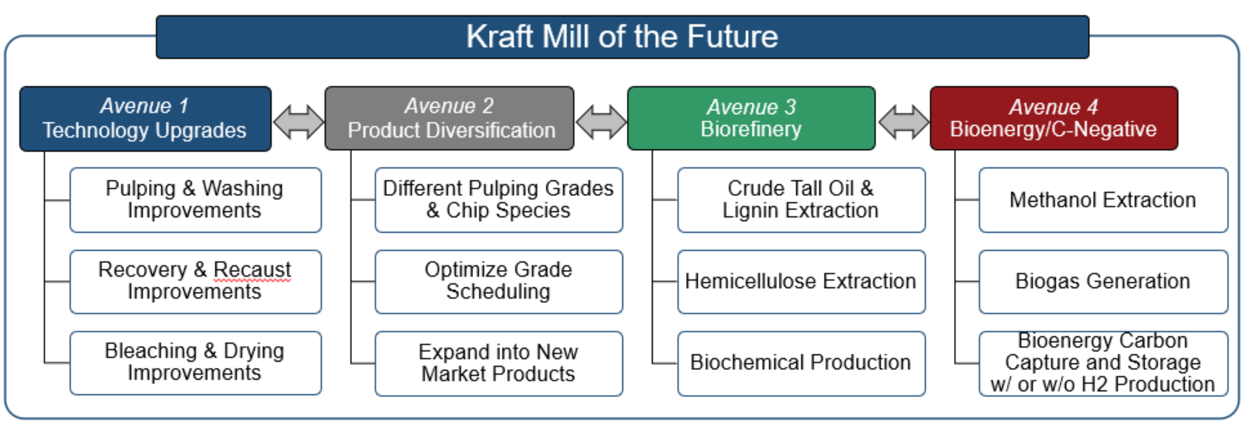

Figure 1: Kraft Mill of the Future Avenues

Technology upgrades in energy intensity departments in Kraft mills can lead to significant energy savings and emission reductions [2,3,4]. By reducing steam and power demand in the mill, fuel consumption can be reduced, leading to lower emissions. The decrease in fuel consumption will also help to preserve biomass, which can be utilized for product diversification and biorefineries instead of solely meeting the energy demands of the Kraft process. The methodology section will provide a description of the technology employed in the digester, brownstock washing, pulp making, and evaporation departments. Maximizing the use of existing technology while also evaluating emerging technologies is crucial to achieve the greatest benefit.

Another avenue mills will have to consider is product diversification and the production of valuable by-products [2]. Implementing new fibrelines and pulp machines will allow mills to modify operating conditions and chemistry to create different products (bleached and non-bleached, softwood and hardwood, packaging, high-strength paper, speciality) and utilize different fibre sources. Further, optimizing grade scheduling allow mills to quickly revise production to capitalize on fluctuating fibre costs and pulp values.

Mills will also need to consider implementing cost-effective biorefineries to meet market requirement and adapt to the decline in paper product demand and intensified competition with other countries [3]. Biorefineries that extract valuable crude tall oil (CTO), lignin, and hemicellulose from black liquor will generate new revenue streams and potentially boost pulp production by debottlenecking steam limited recovery boilers [2,3]. However, pulp production will need to be carefully adjusted considering process bottlenecks (limited additional digester and dryer capacity) without possibly overloading the recovery boiler with heat potentially damaging heat transfer surfaces. If pulp production is not changed, various pathways such as increased energy efficiency, increased power boiler firing, and lowering condensing turbine load to balance the utility system must be assessed to compensate for the loss of heat to the recovery boiler.

The production of biofuels such as methanol, turpentine, biogas, and hydrogen present additional opportunities to enhance revenue while supporting mill decarbonization efforts toward achieving carbon-negative operation [3,4]. By firing these biofuels alongside biomass for process heat demand and power sales, and capturing the biogenic emissions through bioenergy carbon capture (BECCs), Kraft mills can emerge as leaders in achieving carbon neutrality for Canada. Achieving carbon-negative operations will require a combination of efficiency improvements, carbon capture, and transitioning to renewable energy sources [2,4].

However, before implementing technology, pursuing product diversification, establishing biorefineries, and achieving carbon negativity, the current state of existing Kraft mill installations must be considered, as well as the availability, cost, and quality of biomass, which could highly influence the decision-making process for new designs and operating processes. Today, the urgency to reduce reliance on fossil fuels and the rising cost of carbon emissions continue to heighten the value of biomass, which, in turn, increases operating costs for mills firing biomass [3,4]. Hence, it is important to simultaneously consider various future avenues to mitigate the risk of escalating biomass costs and to adapt to rapidly changing costs of fibre and pulp. Sophisticated modelling is required to strategically evaluate different avenues and assess their implications, in order to justify necessary investments, policies, and programs for the future.

METHODOLOGY

This paper will focus exclusively on examining the adoption of various technologies (Avenue 1) to provide comparative results between technologies (independently and in combination) in the context of a generic mill and to illustrate the usefulness of a simulation model that can identify cross-departmental and or cross-technology effects. The methodology of this work is depicted below in Figure 2. First, an assessment of the fuel consumption, emissions, and steam demand of a simulated softwood 900BDMT/d Kraft market pulp mill that is representative of the current state of Canadian Kraft mills was conducted to establish a base case scenario. Then, a comprehensive survey of innovative technologies aimed at reducing energy consumption in high-energy intensity departments was carried out. Finally, six high-impact technologies, discussed below, were integrated into the simulation to evaluate their departmental and cross-departmental effects on energy, steam, emissions, water intake, chemical makeup, biomass consumption, and economics.

Figure 2: Avenue 1 Methodology

Base Case Description and Modelling Approach

The base case of the mill incorporates conventional technology, including a vacuum drum brownstock washer, no oxygen delignification, a six-effect evaporation plant with steam stripping, and typical fibreline de-watering technology. This generic mill modelling was informed by various case studies on real Kraft mills to create a model with similar performance and technology than that is currently being used by industry. In order to ensure that the impacts of each technology could be isolated and analyzed, the following precautions were taken:

1. The operating conditions such as chip feed, Kappa target, causticity, sulphidity, dilution factors were held constant;
2. No additional heat recovery measures were implemented;
3. Natural gas flow to the hog boiler was held constant at 1t/d (more natural gas is typically not required as hog firing is increased as the combustion becomes more self-sufficient).

Figures 3 and 4, presented below, illustrate the base case simulation results for each mill department in a softwood 900BDMT/d Kraft market pulp mill. Additional metrics concerning fibre consumption, pulping targets, and white liquor characterization can be found in the Appendix.

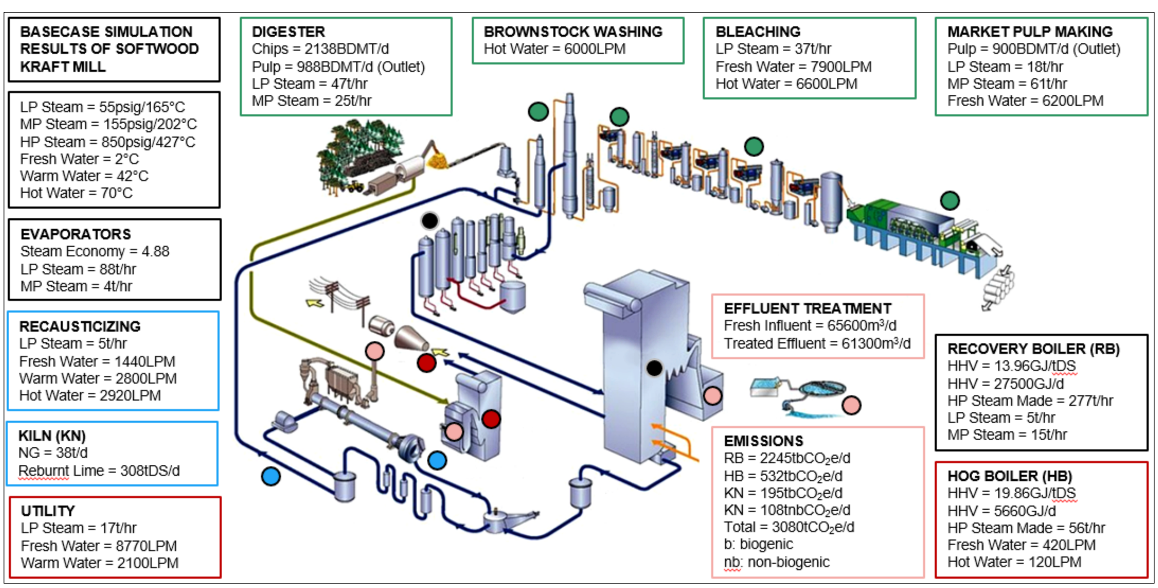

Figure 3: Base case Simulation Results of Softwood Kraft Mill (Modified Image from Kvaerner Pulping)

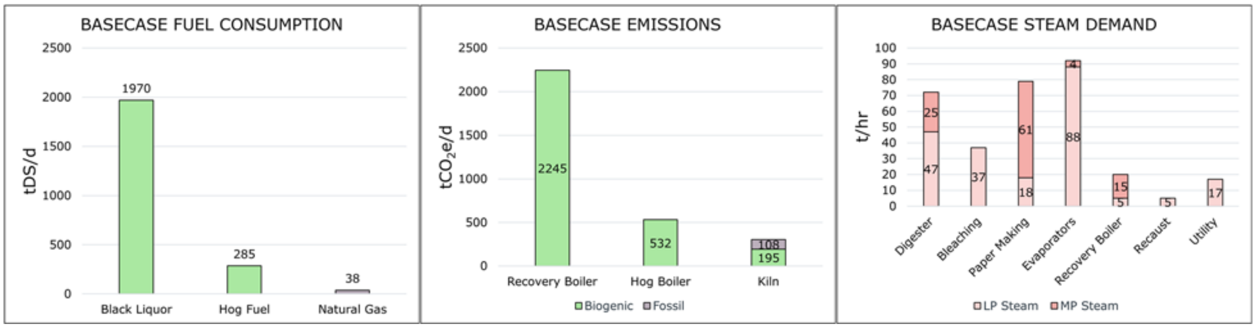

Figure 4: Base Case Energy and Emission Profile

The utilization of a Kraft mill simulation model offers a versatile platform for assessing diverse process configurations, technologies, and operational scenarios prior to implementing any alterations or substantial investments. By leveraging simulation-generated data, the decision-making process is streamlined, enabling comprehensive evaluations that encompass crucial factors such as energy consumption, fiber utilization, water utilization, and chemical requirement. The multifaceted advantages of process simulation are depicted in Figure 5. CADSIM Plus – a draw-based mass and energy balance software capable of handling the integrated nature of the Kraft recovery cycle – was used to model the Kraft mill and various technologies. Beyond CADSIM Plus, alternative modelling software like Aspen Plus, WinGEMS, and MATLAB Simulink can also be harnessed for the purpose of Kraft mill modeling, contributing to a broader spectrum of modelling possibilities.

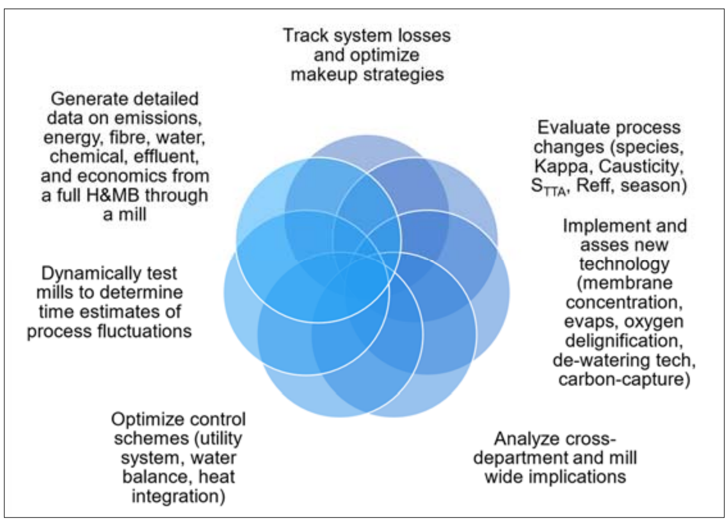

Figure 5: Benefits of Process Simulation

The simulated mill consists of nine departmental linked drawings (see Figure 6) that allow for both departmental and cross-departmental impacts to be characterized, which gives a fuller picture of what is happening to the chemistry and energy flows throughout a mill. The steam balance of the mill is regulated by adjusting the firing rate of hog fuel to the hog boiler, while maintaining natural gas input and turbine output constant. This would be representative of a mill operating optimally to minimize natural gas usage and related emissions, but where turbine output is constrained for various mechanical or electrical reasons. A process flow diagram of the steam and power system is shown below in Figure 7, where the flows to each turbine are held constant (highlighted in blue) and the swing source of steam flows through a pressure reducing valve (highlighted in yellow). In this configuration, as steam demand is reduced with the implementation of technology, the power generation is still maintained at its maximum. This is not the case for other mills that have little to no steam by-pass, meaning steam savings will also result in a reduction of power generation. An overview of key control schemes of the various operating conditions and efficiencies of the simulated Kraft mill is provided in the Appendix.

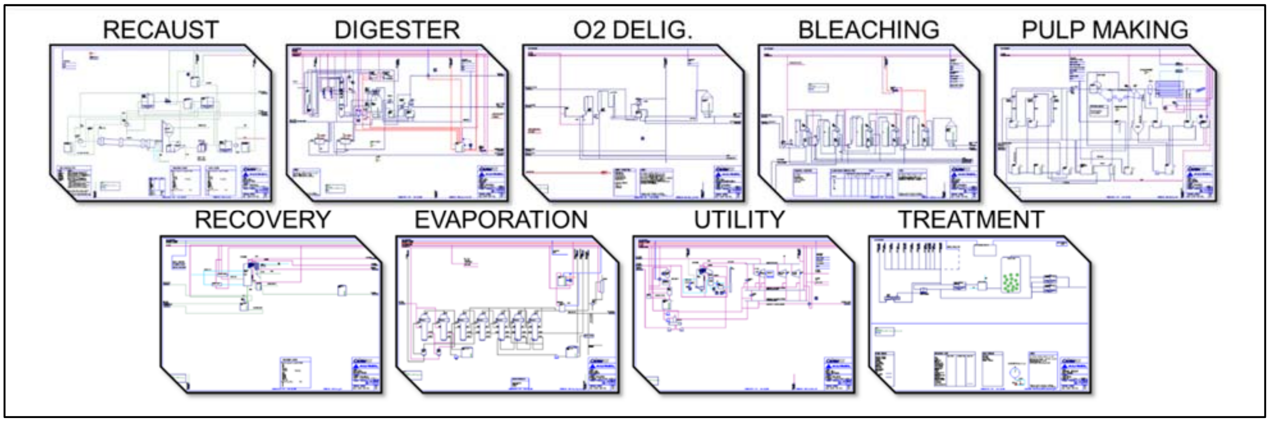

Figure 6: Department Sections of the Model

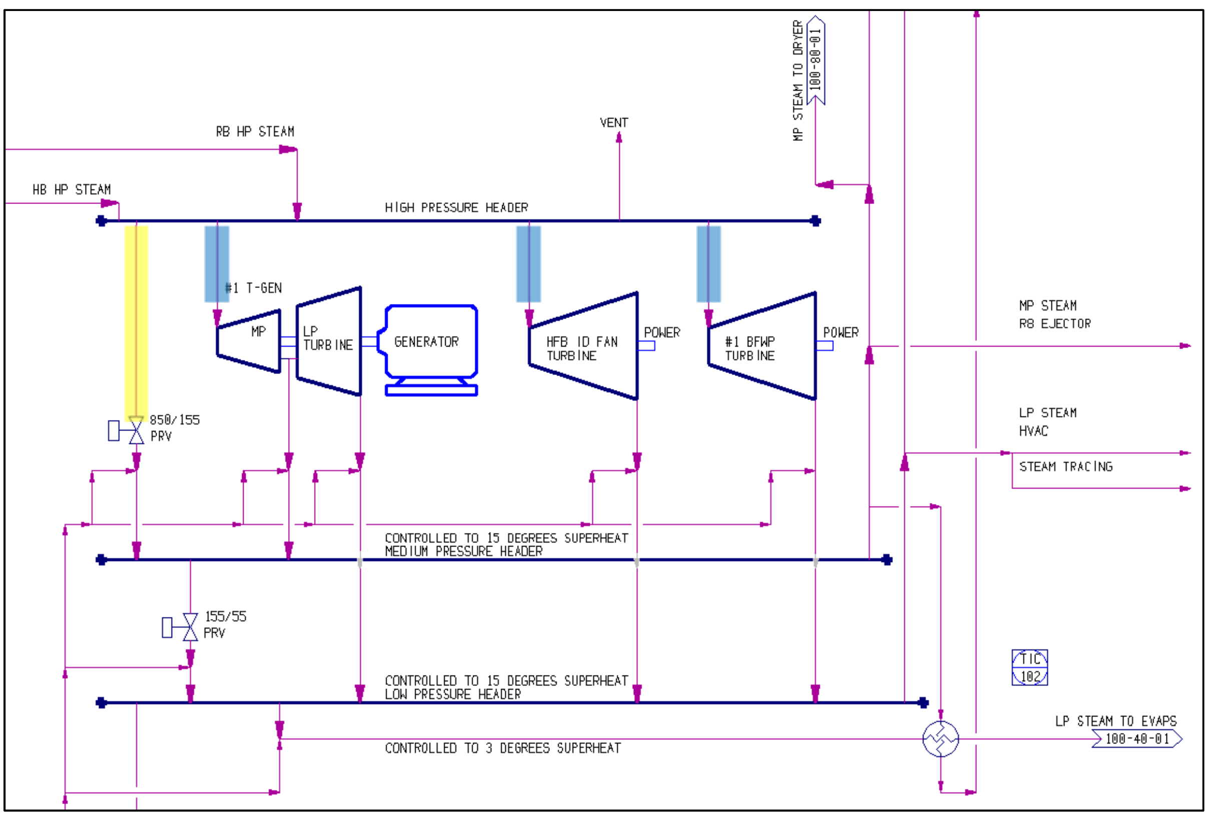

Figure 7: Steam and Power Process Flow Diagram

Technology Selection and Integration Scenarios

The selection of potential technologies must consider the energy demand, process layout, and equipment capacities of each department. Many Canadian Kraft mills are recovery boiler limited, have pulp/paper machines that are constrained by dryers, and have no additional digester capacity. With the understanding of these bottlenecks and the identification of departments with the highest energy demand in the mill, high-impact technologies can be analyzed and implemented now for maximum future benefit. The complete impact of each technology must consider both departmental and cross-departmental implications to ensure that adverse operating conditions are not created.

A thorough evaluation of the benefits and integration challenges associated with each technology candidate is critical. This evaluation encompasses technologies with a proven track record in energy and emission reduction in similar industrial settings, as well as novel technologies with the potential to revolutionize Kraft mills. A combination of case studies, consulting with experts, and discussions with equipment vendors has provided valuable insights into technology selection, modelling approaches, and results evaluation [2,3,4]. After evaluating many different commercially available energy-efficient technologies and ranking them based on their emission reduction potential for boilers, kilns, and dryers, six technology candidates were chosen as low-risk, high-impact opportunities. The selected technology options and their descriptions are provided below in Table I and figures of the modelled technologies are provided in the Appendix. Some other retrofit technologies focusing on oxygen delignification, pulp washing (vacuum drum washers, pressure washers, diffusion washers, belt washers, wash presses, drum displacement washers), and black liquor evaporation (rising film, falling film, direct contact, forced recirculation) are also promising but are not covered in this paper.

Table I: Description of Simulated Technology

Simulated Technology	Technology Description
Base case (BC)	The base case of the mill incorporates conventional technology, including a vacuum drum brownstock washer, no oxygen delignification, a six-effect evaporation plant with steam stripping, and typical pulp de-watering technology.
7 Effect Evaporator Train (7E)	Adding another effect to the base case six-effect train will result in an increased steam economy ($t_{H2OEvapourated}/t_{LiveSteam}$) by providing an additional vapour pass to facilitate black liquor evaporation. This modification enables a more gradual pressure and temperature profile through the train while maintaining the same endpoints. The inclusion of this additional effect enhances the efficiency and performance of the evaporation process in the mill.
WBL Membrane Concentration (MEMB)	The implementation of membrane reverse osmosis for the concentration of weak black liquor (WBL) enables the entry of a higher percentage of dry solids (DS) black liquor into the evaporation plant (increasing from 15%DS to 20%DS). This, in turn, significantly reduces the steam demand for the evaporation process. The simulated technology is based on the graphene oxide membrane process offered by Via Separations® [5]. The membrane has a rejection rate of 99.4%, resulting in a 0.5%DS permeate that is of sufficient purity for utilization in brownstock washing and other washing processes. This technology offers an effective means of concentrating weak black liquor while achieving steam savings in the mill.
Belt displacement washer (BELT)	The belt displacement washer is a technology based on the Chemi-Washer from Kadant Inc [6]. The belt displacement washer, which replaces the conventional vacuum drum brownstock washer with a belt-based multi-stage displacement washing system. The belt displacement washer offers several advantages, including a considerable reduction in shower water requirement by operating at a dilution factor of 1.0 (compared to 2.5 in conventional washers), and an improved displacement ratio from 0.7 to 0.98. To ensure an optimal pressure differential between the hood and suction box, the shower temperature must be increased to 80°C from 70°C. The enhanced washing effectiveness of the belt displacement washer results in cleaner pulp, requiring less bleaching chemical, while more solids are captured in the black liquor. This leads to an increase in organic solids sent to the recovery boiler to produce more HP steam and reduces the need for makeup chemical. The belt displacement washer provides improved washing efficiency, reduces chemical usage, and enhances the overall performance of the pulp washing process.
O_2 delignification with two presses (O2 2P)	The two-stage oxygen delignification simulation with two presses is based on the process offered by Andritz [7]. Oxygen delignification involves the selective oxidation of lignin using sodium hydroxide, oxygen, and pressure. This process allows for a less severe cook in the digester where carbohydrate degradation is minimized, resulting in an increased pulp yield and production. The heat required for the stock entering the oxygen delignification towers is provided by medium-pressure steam. Furthermore, oxygen delignification leads to high lignin removal, resulting in a lower Kappa pulp being sent to bleaching. This reduction in Kappa number leads to a reduced requirement for bleaching chemicals and also results in a reduction in produced effluent. The two-stage oxygen delignification process offers improved delignification efficiency, enhanced pulp quality, and reduced environmental impact of the mill.
Shoe Press (SP)	The shoe press contributes to increased de-watering of the stock entering the dryer, resulting in a reduction in the medium-pressure steam requirement for drying. The shoe press increases the stock consistency from 42% to 45%.
Improved Vacuum Pump (VP)	The improved vacuum pump results in increased de-watering from suction boxes after the headbox. The improved vacuum pup increases consistency of the stock entering the dryer from 42% to 44%. When both the shoe press and improved vacuum pump are activated in the model, the stock consistency entering the dryer raises to 47%.

RESULTS DISCUSSION

The simulation results for each technology listed in Table I will be presented in the order of the objectives: energy, steam, emissions, water, chemical, and economics. For each objective, considering the intricate nature of multi-departmental mass and energy interactions, only the scenarios that result in the largest deviation from base case operation will be described in detail. The simulation results for water, chemical, and economics are found in the Appendix. However, before delving into the specific results, it is important to outline the impact of oxygen delignification, as it influences the final market pulp production and affects the denominators of specific metrics such as energy per tonne of market pulp (GJ/BDMT) and emissions per tonne of market pulp (tCO_2e/BDMT).

Oxygen Delignification

Oxygen delignification offers greater selectivity in dissolving lignin compared to conventional digester cooking, allowing for a higher Kappa target and reducing the need for white liquor loading. In the base case scenario, the digester cook targets a Kappa of 23 (46.2% pulp yield) with an effective alkali charge (EAW%) of 15.8%. In contrast, when oxygen delignification is implemented, the digester cook targets a Kappa of 30 (47.9% pulp yield) with an EAW% of 14.4%. This increase in pulp yield by 1.7% leads to an additional 25BDMT/d of market pulp production (assuming no pulp machine bottleneck), a reduction of 62tDS/d (250LPM) in white liquor flow, and a decrease of 2t/d in natural gas consumption in the kiln compared to the base case scenario (see Figure 8). As the white liquor flow decreases, the required lime addition to green liquor also decreases. This drop in lime addition results in turning down the production rate of the lime kiln, thereby, reducing natural gas consumption. Additionally, the Kappa of stock entering bleaching when oxygen delignification was active is 17, compared to the base case value of 22, which results in reduced bleaching chemical demand.

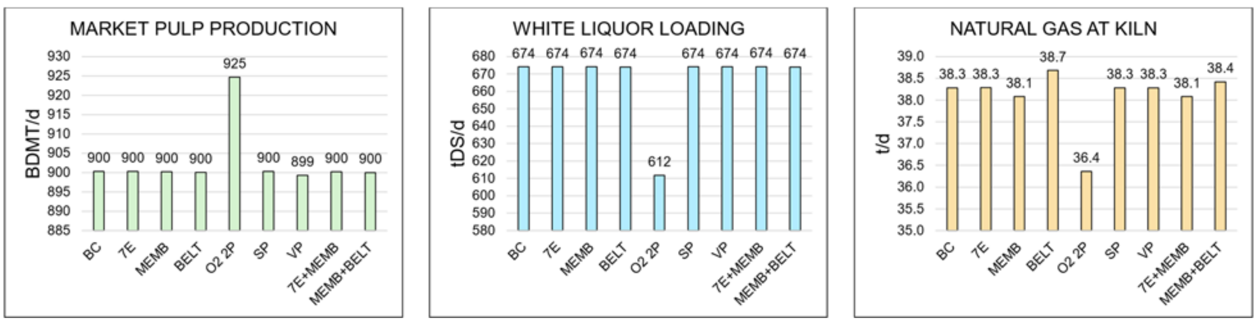

Figure 8: Impact of Oxygen Delignification on Kraft Mill

Energy / Biomass Consumption

The specific thermal energy consumption (black liquor and hog fuel thermal energy, divided by the final market pulp production tonnage) decreased to 34.9GJ/BDMT in the MEMB scenario due to a significant reduction in LP steam to the evaporators (18t/hr). The MEMB scenario reduced hog fuel consumption by 89BDMT/d, representing a 31% decrease compared to the base case consumption. On the other hand, the O2 2P scenario increased hog fuel consumption by 28BDMT/d (see Figure 9). This increase is attributed to the higher demand for medium-pressure steam in the oxygen delignification towers and increased pulp sent to the dryer. However, the specific hog fuel consumption did not increase significantly in the O2 2P scenario due to the overall increased final pulp production.

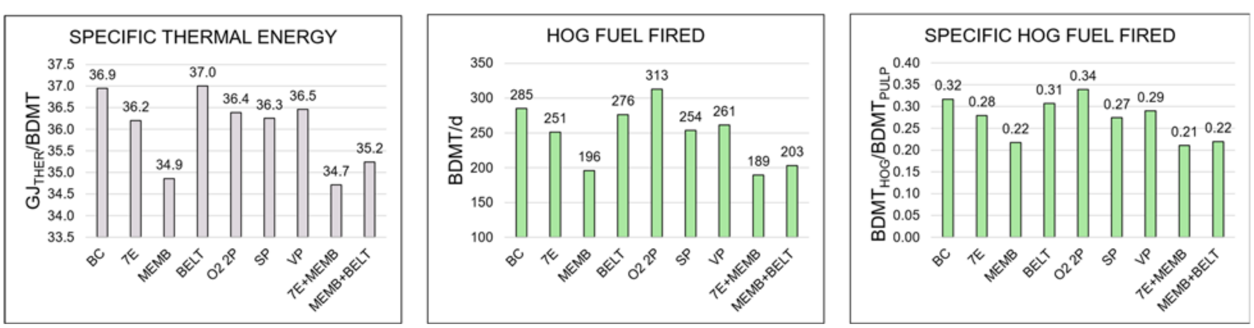

Figure 9: Energy Implications of Technology Integration Scenarios

The digester department hot water network is comprised of the following:

- Warm water (42°C) is used in the weak black liquor cooler, turpentine condensers, and cold blow cooler and the produced hot water (70°C) is sent to the hot water tank;
- Warm water is used as level makeup for the hot water tank and overflow hot water is sent to the recausticizing hot water tank;
- Fresh water (2°C) is used in the brownstock shower cooler (when required to cool the shower to 70°C) and the produced hot water is sent to the hot water tank;
- Hot water from the hot water tank is sent to bleach washing and to a wash heater that uses LP steam to ensure the hot water is at 70°C. The heated wash is then used in oxygen delignification washing and/or brownstock washing. The condensate from the wash heater is returned to the boiler feed water tank.

A cross-departmental system interaction can be observed in the temperature profile of the digester hot water tank in the O2 2P scenario. Specifically, the temperature of the digester hot water tank increases by 4°C compared to the base case temperature of 64°C. This temperature increase is attributed to the hotter filtrate being returned from the oxygen delignification process for use in the brownstock washer as the stock is heated to 82°C before entering the oxygen towers. However, to maintain optimal vacuum within the brownstock vacuum drum, the shower water for the brownstock washer must be cooled down to 70°C. As a result of this shower cooling process, the hot water produced is then sent to the hot water tank, leading to an overall increase in the tank temperature (as depicted in Figure 10). Generally, this example illustrates that if oxygen delignification is integrated into a mill, the heat exchanger network may need to be reconfigured to account for hotter filtrate and brownstock shower temperatures.

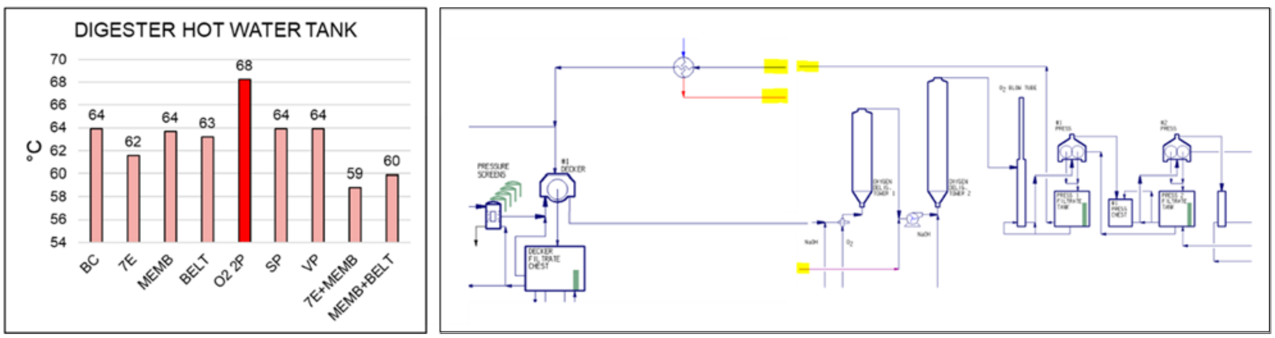

Figure 10: Digester Hot Water Tank Temperature Profile

In the MEMB scenario, another cross-departmental system interaction can be observed in the temperature profile of the evaporator warm water tank (as shown in Figure 11). The implementation of the membrane technology results in a colder evaporator warm water tank. The reason behind this temperature decrease is as follows: with the concentration of weak black liquor to 20%DS, less water needs to be evaporated in the evaporators. Consequently, there is a decrease in the flow of vapour sent to the surface condenser. As a result, there is a reduction in the production of warm water from the condensation of the vapour that is sent to the warm water tank. To maintain the desired level in the tank with less warm water available, more fresh water needs to be introduced into the tank to compensate. This increased addition of fresh water leads to a colder temperature in the evaporator water tank that could be seasonally amplified in winter. This interaction describes a potential warm water deficit that could be created when integrating membrane technology. A condensing turbine or water heater may need to be integrated to produce more warm water.

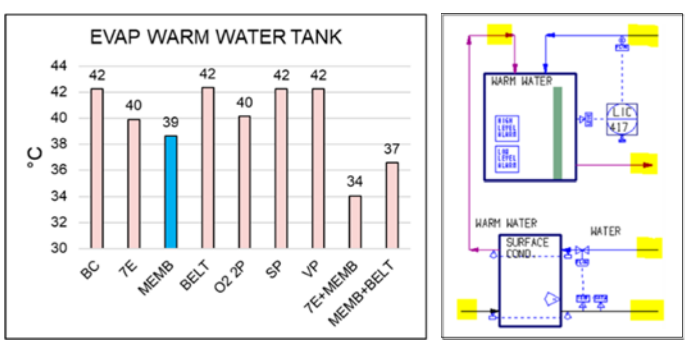

Figure 11: Evaporator Warm Water Tank Temperature Profile

Both of these water tank examples highlight how changes in one department, such as oxygen delignification and membrane reverse osmosis, can influence water flow and temperature dynamics of interconnected systems. Simulation allows for the exploration of these cross-departmental interactions, providing valuable insights into the overall system behavior and dynamics.

Steam Demand

Considering that the HP steam header is the origin of HP, MP, and LP steam throughout the entire mill, the HP demand is representative of the total steam demand of the mill, and it will respond accordingly as different technology is implemented. In the case of the MEMB scenario, a substantial decrease in HP steam demand was observed, reducing it by 19t/hr and achieving a specific HP steam demand of 8.4t_{HP}/BDMT (see Figure 12). This reduction was mainly attributed to the decreased LP steam demand for the evaporators. Conversely, the O2 2P scenario, increased the HP steam demand by 9t/hr. This increase was primarily due to the higher MP steam demand required for the oxygen delignification towers and the increased pulp sent to the dryer. However, it is noteworthy that the specific HP steam demand did not noticeably increase due to the higher final pulp production achieved.

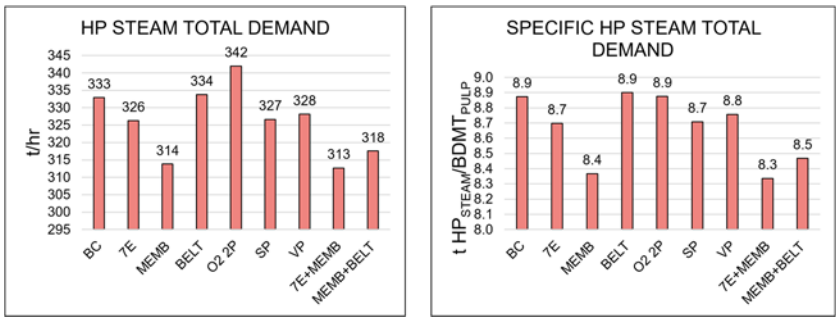

Figure 12: HP Steam Implications of Technology Integration Scenarios

MP steam demand is the summation of dryer, oxygen towers, liquor and some air heater demand. The SP scenario reduced dryer steam demand by 8t/hr by increasing de-watering of stock entering the dryer (see Figure 13). The MEMB scenario lowered MP demand by 20t/hr due to a decrease in LP demand, and the O2 2P scenario increased MP demand by 11t/hr because of a 14t/hr MP demand to the oxygen towers. The total MP demand increase for the O2 2P is not directly equal to the MP demand of the oxygen towers due to cross-departmental impacts. For example, the filtrate produced from the two presses following oxygen delignification is utilized in the shower of the brownstock washer. This hotter filtrate return results in a hotter brownstock washing shower temperature. Consequently, there is a decrease in LP demand for the brownstock shower heater, resulting in a slight decrease in MP demand.

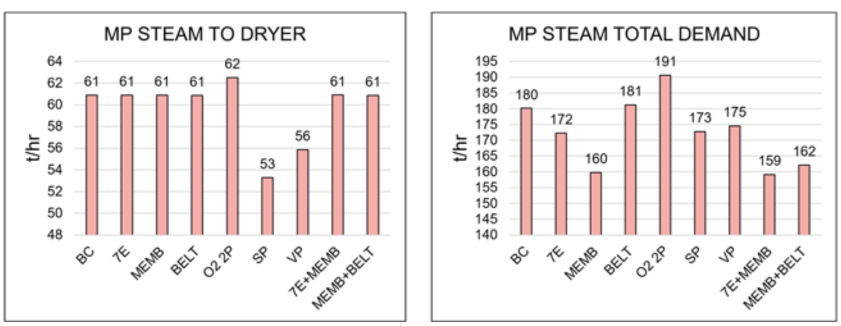

Figure 13: MP Steam Implications of Technology Integration Scenarios

LP steam demand is the summation of evaporator, stripper, deaerator, chip steaming, R8 generator, various heat exchangers (washers, boiler feed water, hot water tanks, stock heaters, recovery boiler air heaters), and pulp machine steam shower demand. The 7E scenario achieved a 5.6 steam economy with the additional vapour pass (resulting in a more efficient use of the same amount of live steam). The 7E+MEMB scenario reduced LP demand to the evaporation plant by 27t/hr and the total LP demand by 29t/hr. However, the BELT scenario increased total LP demand by 7t/hr due to the higher temperature requirement for the shower (refer to Figure 14).

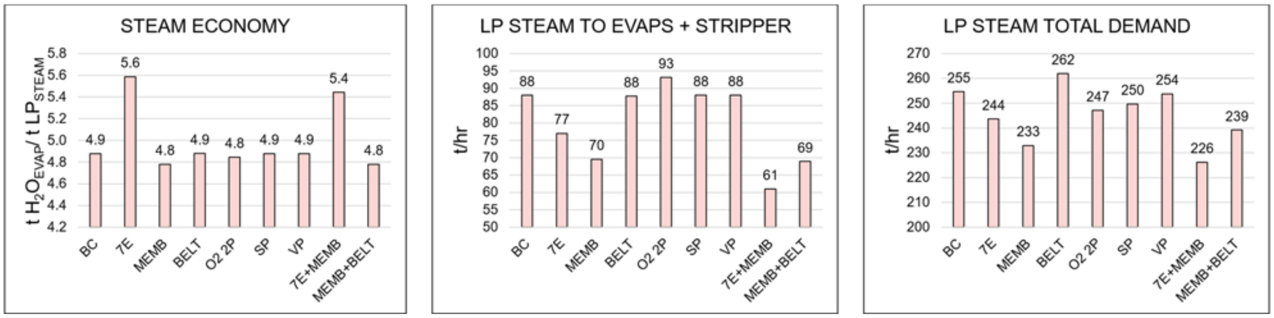

Figure 14: LP Steam Implications of Technology Integration Scenarios

Emissions

The MEMB scenario created a 166tCO_2e/d biogenic emission reduction from the hog boiler (-46% compared to the base case emissions). This reduction is attributed to the decrease of LP steam demand to the evaporators. The O2 2P scenario reduced recovery boiler and kiln biogenic emissions by 36tCO_2e/d and 9tCO_2e/d, respectively (see Figure 15). The reduction in recovery boiler emissions is related to increased pulp yields, which leads to less organic material being burned in the recovery boiler. Further, the reduction in kiln calcination emissions follows the decreased white liquor loading requirement with oxygen delignification. However, the biogenic emissions from the hog boiler increased by 51tCO_2e/d due to the increased firing of hog fuel to compensate for the loss of HP steam production from the recovery boiler, as well as increased MP steam demand to oxygen towers.

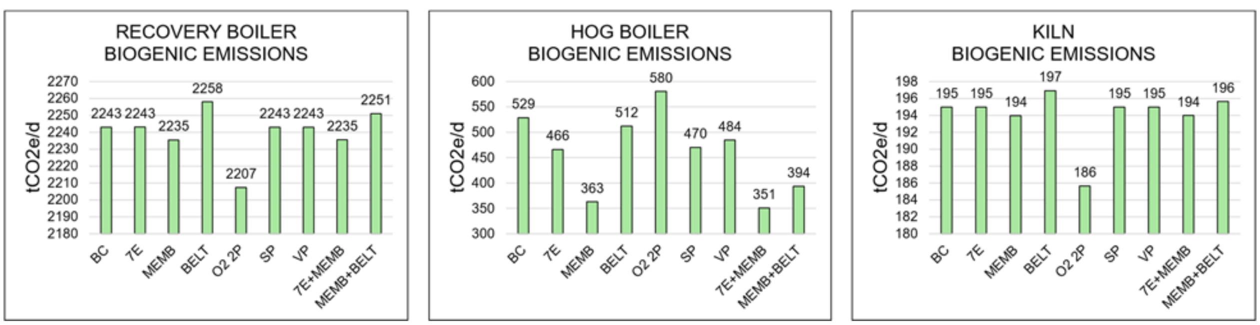

Figure 15: Biogenic Emission Implications of Technology Integration Scenarios

The O2 2P scenario reduced kiln fossil emissions by 6tCO_2e/d with lower white liquor loading (see Figure 16). Kiln fossil emissions are influenced by both white liquor loading and inorganic losses throughout the recovery cycle. For instance, in the case of the BELT scenario, more solids are washed out of the pulp mat, resulting in a higher recovery of inorganics in the smelt, leading to an increased lime requirement for causticizing carbonate. Consequently, more natural gas will be fired in the kiln to produce lime. However, the improved washing performance in the BELT scenario leads to a reduction in makeup chemical requirements to offset losses, and the costs of bleaching decrease due to cleaner incoming stock. When biogenic and fossil emissions are combined to calculate the total emissions for the mill, the MEMB scenario achieves a reduction of 175tCO_2e/d in total emissions and an emissions intensity of 3.21tCO_2e/BDMT (refer to Figure 17).

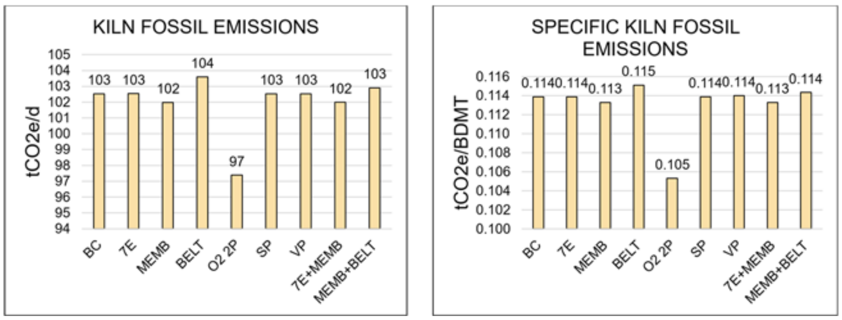

Figure 16: Fossil Emission Implications of Technology Integration Scenarios

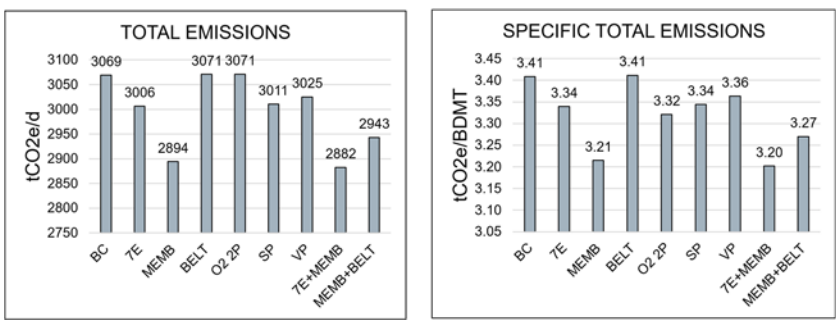

Figure 17: Total Emission Implications of Technology Integration Scenarios

Results Summary and Discussion

A summary of results and changes from base case levels is provided in Tables II-IV. Individual technologies resulted in energy savings of 1.2% to 5.4%, biomass consumption reductions of 8.6% to 31.6%, and emissions reductions of 1.6% to 5.9% from base case levels. The MEMB scenario achieved the largest reductions: 1803GJ/d of thermal energy demand, 90BDMT/d of hog fuel consumption, 19t/hr of HP steam demand, 180tCO_2e/d of total emissions, and 3.6Km^3/d of required water intake for a single technology integration when compared to the base case. The 7E+MEMB scenario achieved the overall lowest hog fuel consumption level at 189BDMT/d and HP steam demand at 311t/hr when integrating two technologies within the mill.

Table II: Results Summary of Simulated Technologies

Technology	[1]Thermal GJ/d	Hog Fuel BDMT/d	HP Steam t/hr	[2]Emission tCO_2e/d	[3]Water Km^3/d	[4]Chemical tDS/d
BC	33221	285	334	3070	66	146
7E	32591	251	326	3007	64	145
MEMB	31418	195	315	2890	62	151
BELT	33302	276	334	3069	65	133
O2 2P	33657	313	343	3070	71	128
SP	32680	247	326	3007	66	146
VP	32824	261	330	3022	66	146
7E+MEMB	31238	189	311	2881	61	151
MEMB+BELT	31716	203	318	2943	62	141

[1]Thermal Energy = $mBL*HHV_{BL}+m_{HogFuel}*HHV_{HogFuel}$
[2]Total Emissions = RB+HB+KN(biogenic+fossil)
[3]Fresh intake water
[4]$O_2+H_2O_2+NaOH+ClO_2+NaClO_3+H_2SO_4+CH_3OH$

Table III: Results Summary of Simulated Technologies (per BDMT)

Technology	Thermal GJ/BDMT	Hog Fuel kgDS/BDMT	HP Steam t/BDMT	Emission tCO_2e/BDMT	Water m^3/BDMT	Chemical kgDS/BDMT
BC	36.9	317	8.9	3.41	73	162
7E	36.2	279	8.7	3.34	71	161
MEMB	34.9	217	8.4	3.21	69	168
BELT	37.0	307	8.9	3.41	72	148
O2 2P	36.4	339	8.9	3.32	77	138
SP	36.3	274	8.7	3.34	73	162
VP	36.5	290	8.8	3.36	73	162
7E+MEMB	34.7	210	8.3	3.20	68	168
MEMB+BELT	35.2	226	8.5	3.27	69	157

Table IV: Change from Base Case Summary of Simulated Technologies

Technology	ΔThermal GJ/d	ΔHog Fuel BDMT/d	ΔHP Steam t/hr	ΔEmission tCO_2e/d	ΔWater Km^3/d	ΔChemical tDS/d
BC	-	-	-	-	-	-
7E	-630 (-1.9%)	-34 (-12%)	-8 (-2.2%)	-63 (-2.1%)	-1.8 (-2.7%)	-1 (-0.6%)
MEMB	-1803 (-5.4%)	-90 (-31.6%)	-19 (-5.6%)	-180 (-5.9%)	-3.6 (-5.5%)	5 (3.7%)
BELT	81 (0.2%)	-9 (-3.2%)	0 (0%)	-1 (0%)	-0.9 (-1.4%)	-13 (-8.7%)
O2 2P	436 (1.3%)	28 (9.8%)	9 (2.7%)	0 (0%)	5.5 (8.3%)	-18 (-12.5%)
SP	-541 (-1.6%)	-39 (-13.6%)	-8 (-2.3%)	-63 (-2.1%)	0 (0%)	0 (0%)
VP	-397 (-1.2%)	-25 (-8.6%)	-4 (-1.2%)	-48 (-1.6%)	-0.1 (-0.1%)	0 (-0.1%)
7E+MEMB	-1983 (-6%)	-96 (-33.8%)	-23 (-6.7%)	-189 (-6.2%)	-4.5 (-6.9%)	5 (3.7%)
MEMB+BELT	-1505 (-4.5%)	-82 (-28.8%)	-16 (-4.8%)	-127 (-4.1%)	-4.0 (-6.0%)	-5 (-3.1%)

A comparison between the departmental and cross-departmental implications and system integration considerations for each technology and several combinations of technologies is provided below in Table V. Bolded comments are also provided within Table V to describe overlapping effects from combining technologies.

Table V: Comparison of Each Simulated Technology

Technology	Departmental Implications	Cross-departmental Implications	System Integration Considerations
7E	11t/hr decrease in LP steam to evaporator department. 2°C colder evaporator warm water tank from lower surface condenser load. 8t/hr increase in combined condensate flow.	2°C colder evaporator warm water tank leads to: 0.6t/hr increase in LP steam to recausticizing hot water tank, 2t/hr increase in LP steam to brownstock shower heater, and 2t/hr increase in LP steam to bleach shower heater.	Additional warm water may need to be generated from a condensing turbine or hot water heater due to a decreased production of warm water from the evaporator department. Potential reuse of combined condensate for water and energy reduction.
MEMB	18t/hr decrease in LP steam to evaporator department. 73t/hr decrease in combined condensate flow. 4°C colder evaporator warm water tank from lower surface condenser load.	20tDS/d increase in entrapped solids with pulp, resulting in 2tDS/d increase in bleaching chemical. No LP steam required for brownstock wash heater due to heat from permeate. 7t/hr of water required to cool brownstock shower to 70°C. 2t/d additional caustic required from losses with permeate.	May need several membrane systems in series and parallel to provide sufficient concentration at the full flow rate of all weak black liquor. Optimize the combination of weak black liquor sources to create ideal feed %DS to membrane systems. Utilize permeate in pulp washing processes.
BELT	14tDS/d increase in solids being captured in weak black liquor. 300t/d decrease in required shower water flow. 13t/hr increase in LP steam demand to heat shower temperature to 80°C.	Pulp is 4°C hotter entering bleaching, resulting in 7t/hr less LP steam demand in bleaching department. Cleaner pulp with 55tDS/d less entrapped solids required 4tDS/d less bleaching chemical. 14tDS/d increase in solids fired in recovery boiler resulting in 3t/hr increase in HP steam production. 3.5t/d caustic savings from improved pulp washing.	Dilution factors of washing units before and after the BELT will need to be adjusted to allow for the washing water savings to be realized. The BELT requires an 80°C shower so an LP wash heater may be required. Utilize combined condensate for water and energy reduction then explore heat recovery opportunities from waste streams to decrease the demand for LP steam.
O2 2P	1.7% increase in pulp yield, resulting in 25BDMT/d increase in final pulp production. Requires 14t/hr MP steam to oxygen towers and 35tDS/d oxygen delignification chemical.	No LP steam required for brownstock wash heater due to heat from oxygen delignification filtrate return. 95t/hr of cooling water required to cool brownstock shower, resulting in a 4°C hotter digester hot water tank, creating a 3t/hr LP steam decrease to bleach wash heaters. Lower Kappa to bleaching department resulted in a 9tDS/d decrease in bleaching chemical demand, and 28tDS/d decrease in solids sent to effluent treatment. 2t/hr increase in MP steam to dryer. 5t/hr increase in LP steam to evaporator department. Firing rate at recovery boiler decreased by 40tDS/d, black liquor HHV increased to 14.16GJ/tDS from 13.96GJ/tDS from increased organic to inorganic ratio, and boiler thermal efficiency increased by 1%, resulting in a 4t/hr increase in HP steam production. 2t/d decrease in natural gas firing in lime kiln from lower white liquor loading.	Will need to consider if all fibreline and pulp/paper making units can handle an increase in pulp production rate without compromising performance. Retrofit water and heat exchanger network to minimize water and energy consumption.
SP+VP	5% increase in stock consistency entering the dryer, resulting in a 12t/hr MP steam saving. 1t/hr increase in LP steam to department to compensate for less condensate from MP steam.	No significant cross-departmental implications.	Integrating a shoe press may require relocation/ reconfiguration of the dryer. White water system may require a reconfiguration. Optimizing the vacuum pump system could also lead to electricity savings and water reduction.

Table V: Comparison of Each Simulated Technology (Continued)

Technology	Departmental Implications	Cross-departmental Implications	System Integration Considerations
7E+MEMB	27t/hr decrease in LP steam to evaporator department. 8°C colder evaporator warm water tank from lower surface condenser load. 67t/hr decrease in combined condensate flow.	8°C colder evaporator warm water tank leads to: 2t/hr increase in LP steam to recausticizing hot water tank, 2t/hr increase in LP steam to brownstock shower heater, and 4t/hr increase in LP steam to bleach shower heater. **The permeate provides heat for brownstock shower, but the evaporator warm water tank is 8°C colder, resulting in a need for trim heat.** See MEMB above for remaining implications.	See 7E and MEMB suggestion above.
7E+BELT	11t/hr decrease in LP steam to evaporator department. 4°C colder evaporator warm water tank from lower surface condenser load. 7t/hr increase in combined condensate flow. 16t/hr increase in LP steam demand to heat shower temperature to 80°C (**increased LP steam demand due to colder evaporator warm water tank**). See BELT above for remaining implications.	4°C colder evaporator warm water tank leads to: 1t/hr increase in LP steam to recausticizing hot water tank and 4t/hr increase in LP steam to bleach shower heater. Pulp is 4°C hotter entering bleaching, resulting in 4t/hr less LP steam demand in bleaching department. See BELT above for remaining implications.	See 7E and BELT suggestion above.
7E+O2 2P	6t/hr decrease in LP steam to evaporator department (**less steam savings due to water introduced from oxygen delignification washing**). See O2 2P above for remaining implications.	No LP steam required for brownstock wash heater due to heat from oxygen delignification filtrate return. 89t/hr of cooling water required to cool brownstock shower. See O2 2P above for remaining implications.	See O2 2P suggestion above.
MEMB+BELT	18t/hr decrease in LP steam to evaporator department. 73t/hr decrease in combined condensate flow. 5°C colder evaporator warm water tank from lower surface condenser load. 5tDS/d increase in solids being captured in weak black liquor (**decreased washing performance from dirtier permeate as washing solution**). 300t/d decrease in required shower water flow when operating BELT. 9t/hr increase in LP steam demand to heat shower temperature to 80°C (**less steam demand due to heat provided by permeate**).	5°C colder evaporator warm water tank leads to: 1t/hr increase in LP steam to recausticizing hot water tank and 4t/hr increase in LP steam to bleach shower heater. Pulp is 3°C hotter entering bleaching, resulting in 4t/hr less LP steam demand in bleaching department. Cleaner pulp with 31tDS/d less entrapped solids required 2tDS/d less bleaching chemical (**less solids are washed out of pulp when using permeate**). 5tDS/d increase in solids fired in recovery boiler resulting in 1t/hr increase in HP steam production. 1t/d caustic savings.	See MEMB and BELT suggestion above.
MEMB+O2 2P	12t/hr decrease in LP steam to evaporator department (**less steam savings due to water introduced from O2 delig. washing**). 55t/hr decrease in combined condensate flow. See O2 2P above for remaining implications.	No LP steam required for brownstock wash heater due to heat from permeate and oxygen delignification filtrate return. 108t/hr of cooling water required to cool brownstock shower. Remaining implications are the same as O2 2P above with a slight increase in bleaching chemical demand and solids sent to effluent treatment and slight decrease in solids fired due to solids lost in permeate.	See O2 2P suggestion above.

The thermal energy consumption and total emissions for various combinations of technologies organized from lowest to greatest is provided below in Figure 18.

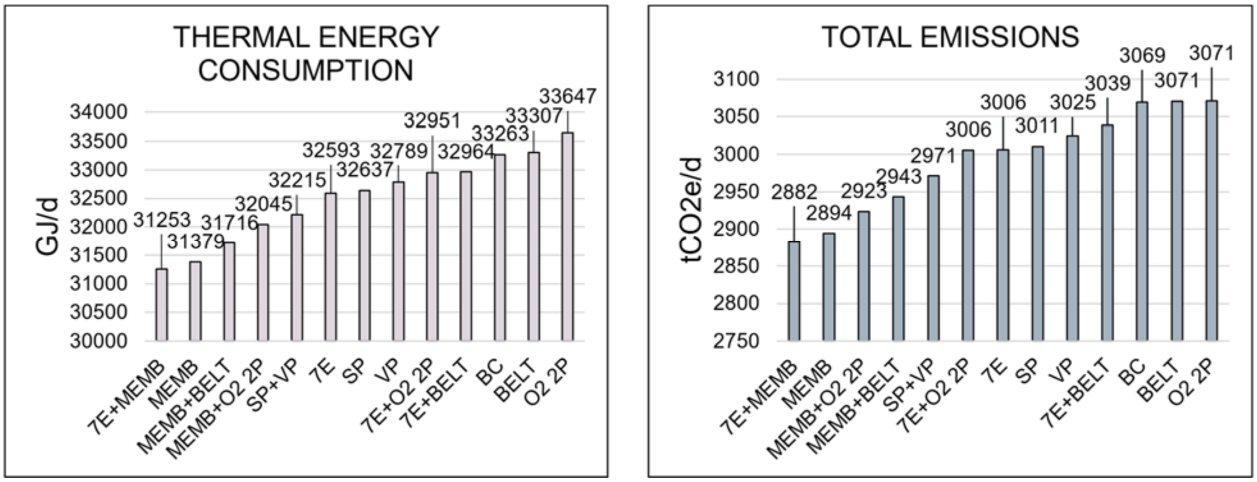

Figure 18: Energy and Total Emissions Technology Comparison

The 7E+MEMB combination yielded the lowest thermal energy consumption and total emissions at 31253GJ/d and 2882tCO2e/d, saving 2010GJ/d and 187tCO2e/d compared to the base case mill. These significant savings are attributed to reduced LP steam usage in the evaporators and improved steam economy. Integrating all technologies (7E+MEMB+BELT+O2 2P+SP+VP) further reduced energy consumption to 29510GJ/d and total emissions to 2680 tCO2e/d, resulting in even greater energy savings of 3750GJ/d and total emissions savings of 390 tCO2e/d compared to the base case mill.

Table V reveals a clear synergy between MEMB, BELT, and O2 2P combinations. MEMB efficiently saves LP steam in the evaporators department, while hot permeate provides heat to the BELT and oxygen delignification washes, reducing LP steam needs in the pulp washing departments. In the MEMB+BELT combination, the slight reduction in BELT washing efficiency due to permeate use is offset by steam savings required to heat the shower to 80°C.

While the BELT enhances washing performance, it consumes more thermal energy and generates emissions due to additional LP steam requirements for heating. Nonetheless, the benefits include increased HP steam production, reduced hog fuel consumption, and lower demand for makeup and bleaching chemicals, as well as decreased effluent loading. This leads to a noteworthy $7K/d reduction in operating costs (for detailed economic discussion, refer to the Appendix).

In the case of 7E, MEMB, and 7E+MEMB, the LP steam savings in the evaporator department are significantly enhanced. However, this leads to a reduction in warm water production from the evaporator department, potentially causing a shortage of warm water depending on how the permeate is re-used. This, in turn, lowers the temperatures of other mill water tanks, creating a higher demand for LP steam in other departments. Further, the 7E + O2 2P combination illustrates how improved efficiency in one department can be masked by process changes in another. Although there are steam savings from increased steam economy, they are offset by the additional water introduced from oxygen delignification washing.

Combining technologies can lead to diverse outcomes: it may amplify benefits, pose challenges, or achieve balanced solutions that compromise certain aspects for overall mill savings. Additionally, the combined effects might not always yield immediate apparent savings. The integration of these technologies will necessitate a careful reconfiguration of the heat and water networks to optimize their usage, avoiding unnecessary heating and subsequent cooling of water for different units. Implementing equipment and new piping connections to optimize the cooling water system together with the warm and hot process water may also be necessary. Mills can greatly improve their investment decisions by adopting simulation modelling, as demonstrated in this study. Comprehensive modelling that calculates all technology integration implications when informed with specific bottlenecks and aging equipment, can allow mills to strategically plan and execute technically feasible retrofits that lead to substantial enhancements in overall mill efficiency.

CONCLUSION

A mill-wide simulation model has been developed to evaluate various technologies, taking into account the complex and interconnected nature of the Kraft recovery cycle. This simulation provides a comprehensive assessment of each technology, considering their effects on energy, steam, emissions, water, chemicals, and economics. By capturing the interdependencies within the mill, the model helps identify potential bottlenecks and optimization opportunities. In each scenario, consistent operating conditions were maintained, and no additional heat recovery measures were implemented. Results have shown that various technologies and combinations thereof can have important and unexpected cross-departmental implications that would be difficult to predict without a mill-wide simulation model, for example when the balance of warm and hot water is involved. It is important to note that the performance of each technology will depend on the specific context of the mill, including departmental bottlenecks, the initial efficiency of the mill, and the maturity of the technology implemented. The simulation model also enables scenario analysis, allowing for comparisons of different process configurations and technology combinations to identify the most effective and sustainable solutions. Future work will expand to explore the implications of other technologies such as waste heat hog fuel drying, lime kiln fuel substitution, heat pumps, as well as product diversification, biorefineries, and avenues for carbon negativity. Process simulation will continue to play a crucial role in enhancing our understanding of process interactions, supporting data-driven decision-making for policy direction, and accelerating efforts to reduce emissions, improve sustainability, and secure a competitive future for Kraft mills.

Acknowledgements

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APPENDIX

Additional Base Case Description

Figure 19 and Table VI below, provide more detailed base case simulation results that include fibre consumption, pulping targets, white liquor loading and characteristics, chemical demand, recovery boiler firing rate and reduction efficiency, boiler thermal efficiencies, effluent BOD loading, and additional results. Table VII below provides key control schemes of the various operating conditions and efficiencies of the simulated Kraft mill.

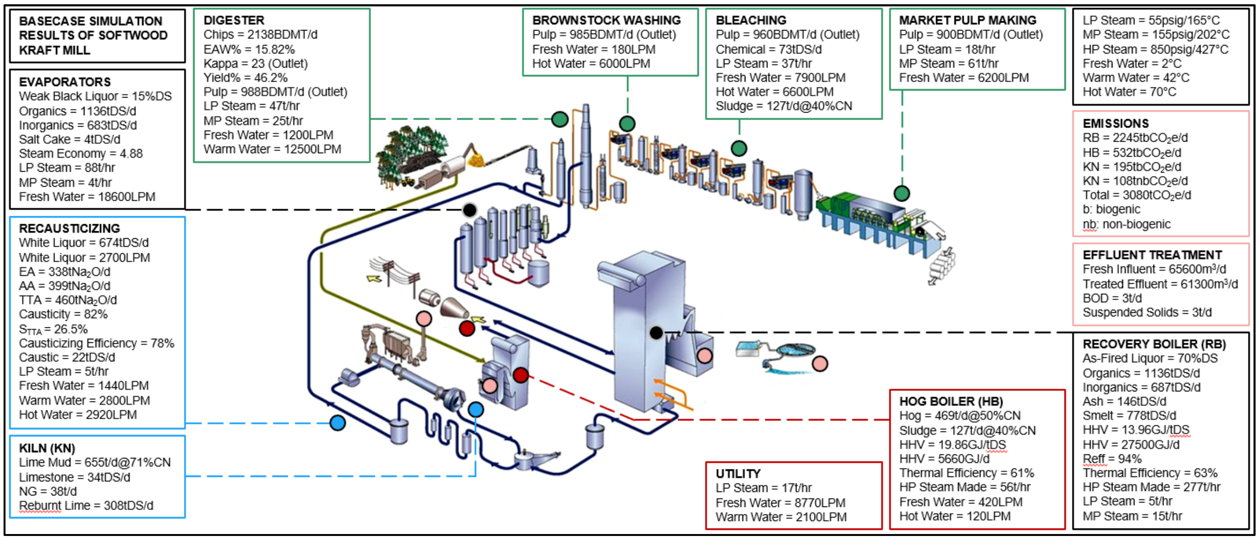

Figure 19: Base Case Simulation Detailed Results of Softwood Kraft Mill (Modified Image from Kvaerner Pulping)

Table VI: Base Case Simulation Detailed Results

Department	Simulation Results
Digester	Chips = 2138BDMT/d, EAW% = 15.82%, Kappa = 23 (Outlet), Yield = 46.2%, Pulp = 988BDMT/d, LP Steam = 47t/hr, MP Steam = 25t/hr, Fresh Water = 1200LPM, Warm Water = 12500LPM
Brownstock Washing	Pulp = 985BDMT/d (Outlet), Fresh Water = 180LPM, Hot Water = 6000LPM
Bleaching	Pulp = 960BDMT/d (Outlet), Chemical 73tDS/d, LP Steam = 37t/hr, Fresh Water = 7900PLM, Hot Water = 6600LPM, Sludge = 127t/d@40%CN
Market Pulp Making	Pulp = 900BDMT/d (Outlet), LP Steam = 18t/hr, MP Steam = 61t/hr, Fresh Water = 6200LPM
Evaporators	Weak Black Liquor = 15%DS, Organics = 1136tDS/d, Inorganics = 683tDS/d, Salt Cake = 4tDS/d, Steam Economy = 4.88, LP Steam = 88t/hr, MP Steam = 4t/hr, Fresh Water = 18600LPM
Recovery Boiler	As-Fired Liquor = 70%DS, Organics = 1136tDS/d, Inorganics = 687tDS/d, Ash = 146tDS/d, Smelt = 778tDS/d, HHV = 13.96GJ/tDS, HHV = 27500GJ/d, Reff = 94%, Thermal Efficiency = 63%, HP Steam Made = 277t/hr, LP Steam = 5t/hr, MP Steam = 15t/hr
Hog Boiler	Hog = 469t/d@50%CN, Sludge = 127t/d@40%CN, HHV = 19.86GJ/tDS, HHV = 5660GJ/d, Thermal Efficiency = 61%, HP Steam Made = 56t/hr, Fresh Water = 420LPM, Hot Water = 120LPM
Utility	LP Steam = 17t/hr, Fresh Water = 8770LPM, Warm Water = 2100LPM, HP Steam to MP/LP Turbine = 210t/hr, MP Turbine = 16MW, LP Turbine = 5MW, HP Steam to HFB ID Fan Turbine = 6t/hr, HFB ID Fan Turbine = 0.6MW, HP Steam to BFWP Turbine = 28t/hr, BFWP Turbine = 3MW
Recausticizing	White Liquor = 674tDS/d, White Liquor = 2700LPM, EA = 338tNa_2O/d, AA = 399tNa_2O/d, TTA = 460tNa_2O/d, Causticity = 82%, S_{TTA} = 26.5%, Causticizing Efficiency = 78%, Caustic = 22tDS/d, LP Steam = 5t/hr, Fresh Water = 1440LPM, Warm Water = 2800LPM, Hot Water = 2920LPM
Kiln	Lime Mud = 655t/d@71%CN, Limestone = 34tDS/d, NG = 38t/d, Reburnt Lime = 308tDS/d
Emissions	RB = 2245tbCO_2e/d, HB = 532tbCO_2e/d, KN = 195tbCO_2e/d, KN = 108tnbCO_2e/d, Total = 3080tCO2e/d
Effluent Treatment	Fresh Influent = 65600m3/d, Treated Effluent = 61300m3/d, BOD = 3t/d, Suspended Solids = 3t/d

Table VII: Key Control Schemes of Kraft Mill Simulation Model

Operating Condition / Efficiency	Control Scheme
Pulping	Yield is a function of Kappa and white liquor loading is a function of yield. As Kappa decreases from a more severe cook (increased time, temperature, and white liquor loading), yield decreases (resulting in an increase in organic solids to the recovery boiler) and the inorganic solids sent to the recovery boiler also increases from increased white liquor loading.
Washing	Washing efficiency is a function of dilution factor, stock consistency entering and exiting units, and typical mat breakthrough. The pulp washing stages include digester, atmospheric and pressurized diffusion washing, brownstock washing, BELT, oxygen delignification washing, and bleach washing.
Causticity	Treated white liquor causticity is a function of the extent of the slaking and causticizing reactions and the amount of limestone makeup.
Sulphidity (TTA basis)	The sulphidity (TTA basis) is controlled by the rate of saltcake makeup added to weak black liquor.
Reduction Efficiency	The reduction efficiency of the smelt is set to 94%.
Black Liquor HHV	The higher heating value (HHV) of the as-fired black liquor in GJ/tDS is calculated as the energy supplied by all organics divided by the total dry solids firing rate at the recovery boiler.
Boiler Thermal Efficiency	The thermal efficiency of all boilers is calculated from a full mass and energy balance of all streams entering and exiting boilers.
Natural Gas to Kiln	Natural gas is controlled to maintain a reasonable flue gas temperature of 250°C.
Inerts Control	Inerts are controlled with purges that maintain potassium concentration to 2wt%DS and chlorine concentration to 2.2wt%DS in the treated white liquor.
Electrical Consumption	The mills electrical consumption is calculated based on empirical equations based on pulp production for each department.
OPEX Estimate	The mills operating cost (OPEX) considers the cost of chips, hog fuel, fossil fuels, electricity purchases, chemicals/makeup, fresh water, effluent treatment, and fossil emission taxes.
Steam Balance	The firing rate of hog fuel to the hog boiler serves as the slack in the system that will adjust to balance the global steam production and demand as different technology is integrated.

Technology Selection and Integration Scenarios

Figure 20-23 below provide diagrams for the various technologies that have been integrated into the simulation model. Note that the shoe press and improved vacuum pump does not show up as a visible change in the flowsheet but rather modifies various efficiency metrics to improve pulp de-watering.

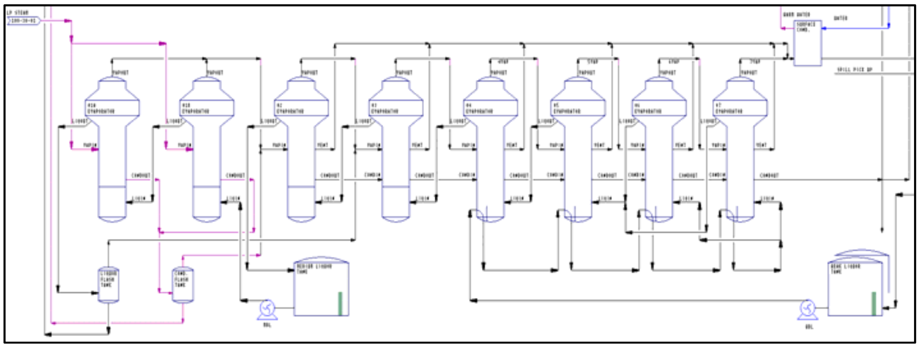

Figure 20: 7 Effect Evapourator Train (7E)

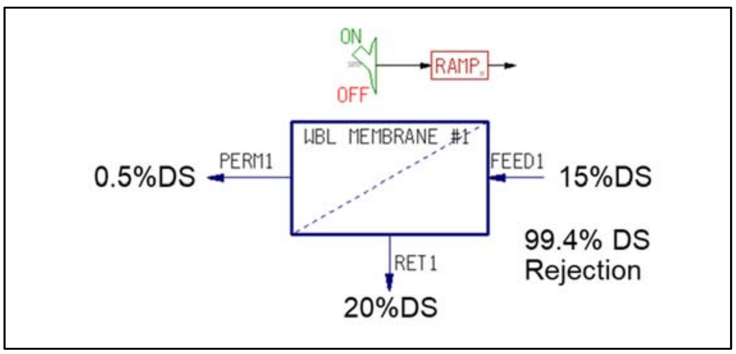

Figure 21: WBL Membrane Concentration (MEMB)

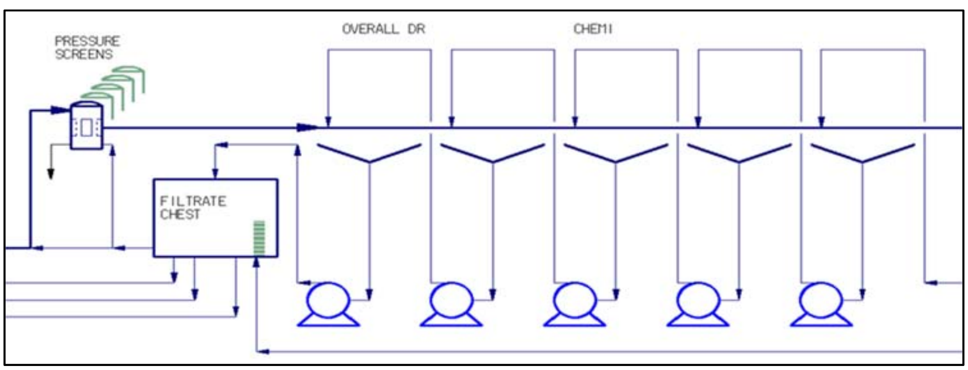

Figure 22: Belt Displacement Washer (BELT)

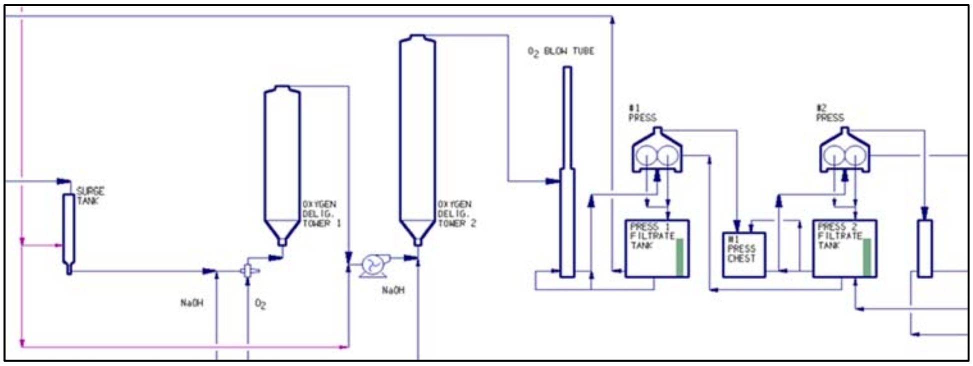

Figure 23: O_2 delignification with two presses (O2 2P)

Additional Simulation Results

The simulation results for water demand, chemical demand, and economic implications are detailed below.

Water Demand

Water demand is the sum of washing, cooling, boiler feed water, and level makeup demand. In the O2 2P scenario, the water influent increased by 5000m^3 due to higher pulp production, which required more washing water, and an increase in steam demand (leading to a direct increase in boiler feed water demand). The BELT scenario did not result in a significant decrease in water influent because the dilution factors of the washing units before and after the BELT were not altered in keeping with a fair comparison of each technology by not changing any operating conditions. To fully realize the benefit of reduced washing water demand from the BELT, the dilution factors throughout the mill need to be adjusted to achieve similar overall washing performance as the base case. The MEMB scenarios achieved a 69m^3/BDMT specific water demand due to decreased LP steam demand for the evaporators (requiring less boiler feed water makeup) and the re-use of permeate in brownstock washing (requiring less washing water makeup) (see Figure 24).

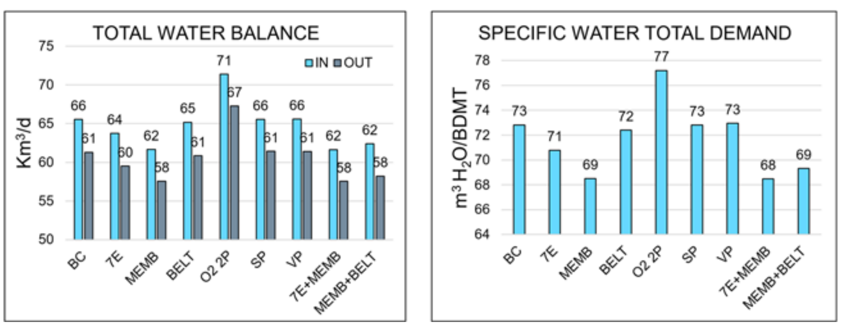

Figure 24: Water Implications of Technology Integration Scenarios

Chemical Demand

Chemical demand is the summation of caustic (NaOH), saltcake (Na_2SO_4), oxygen delignification (O_2+NaOH), and bleaching (O_2+H_2O_2+NaOH+ClO_2+$NaClO_3$+H_2SO_4+CH_3OH) chemical demand, aggregated by mass as dissolved solids. The BELT scenario reduced total chemical demand by 11tDS/d by producing cleaner pulp entering bleaching. The O2 2P scenario decreased the total chemical demand by 17tDS/d, achieving a chemical intensity of 138kgDS/BDMT (see Figure 25). These chemical savings can be attributed to a lower Kappa value of 17 for the pulp entering the bleaching department, compared to the base case Kappa value of 22.

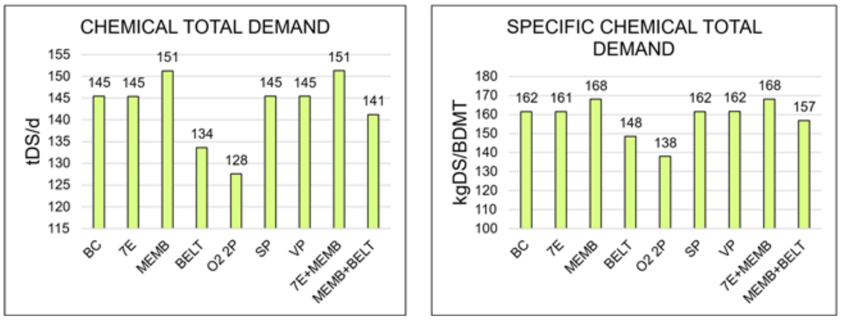

Figure 25: Chemical Implications of Technology Integration Scenarios

Economics

The simulated mill operating costs (OPEX) include the costs of chips, hog fuel, natural gas, purchased power (power demand – power production), chemicals (see chemical demand description), limestone makeup, freshwater influent, demineralization of boiler feed water, effluent treatment, fossil emission tax, and various miscellaneous costs. The unit cost of each operating cost is provided below in Table VIII. The MEMB+BELT scenario achieved the lowest OPEX at $537K/d, resulting in a $11K/d saving compared to the base case OPEX (refer to Figure 26). The O2 2P scenario increased revenue by $32K/d at $1288/BDMT and profit by $36K/d and achieved a specific OPEX of $587/BDMT. The economic improvement in the O2 2P scenario can be attributed to the additional 25BDMT/d of pulp production. However, it is important to note that achieving an increase of 25BDMT/d production may face various departmental bottlenecks.

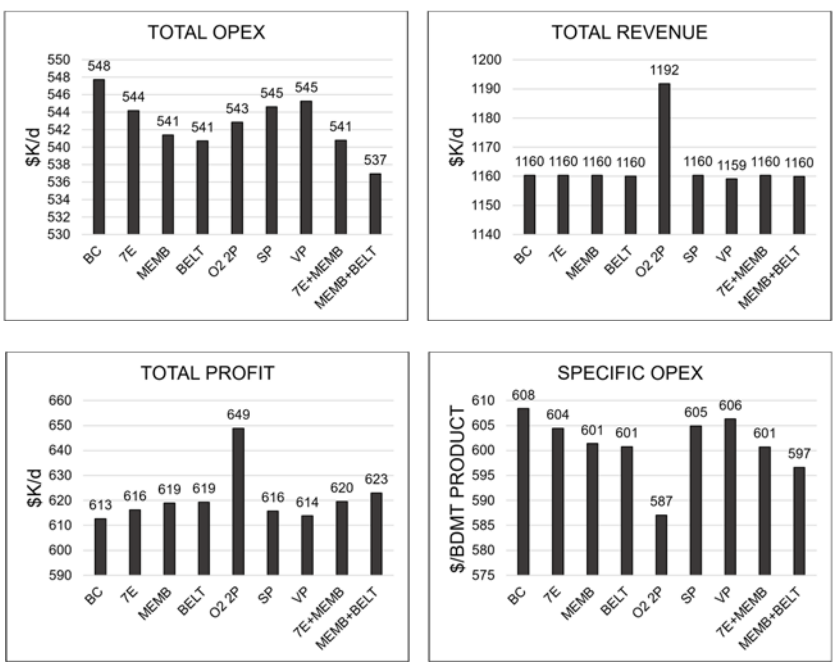

Figure 26: Economic Implications of Technology Integration Scenarios

Table VIII: OPEX Unit Costs

Unit Costs \$CAD
Chips = \$200/BDMT, Hog Fuel = \$100/BDMT
Natural Gas = \$3.50/GJ, Purchased Power = \$0.07/MWh
$NaOH$ = \$600/t, $NaClO_3$ = \$700/t, H_2SO_4 = \$150/t, CH_3OH = \$480/t, O_2 = \$35/t, Limestone = \$35/t
Freshwater Influent = \$0.04/t, Demineralization = \$1.00/t, Effluent Treatment = \$0.04/t, Fossil Emission Tax = \$30/tCO_2e applied to all fossil emissions, Miscellaneous Cost = \$1.00/ADMT