Full-scale operation of a membrane-based black liquor concentrator

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ABSTRACT: For years, black liquor concentration by reverse osmosis has been an aspiration for reducing mill energy consumption and costs. Building on a 2023 report of an 81% reduction in the energy intensity for concentrating black liquor using its membrane platform at the pilot scale, this paper reports on the fabrication, installation, startup, and operation of the world's first full-scale membrane-based black liquor concentration system at the International Paper Grande Prairie mill in Canada.

The majority of the membrane modules in this system have reliably exceeded permeability expectations by more than 50%. In addition to strong membrane performance, the system has been a significant source of learnings for material specifications and system design. Incorporating these learnings and comparing to typical multiple effect evaporators, the system demonstrates a 43% reduction in capital cost for the same capacity, a 30% reduction in the lifetime cost of removing water from black liquor, and an 86% reduction in energy use. The impact on washer optimization was also considered, and net energy and chemical costs were reduced by US$3.8 and US$6.8/a.d. metric ton for a typical brown and bleach mill, respectively, when incorporating this technology. Completed in less than 12 months, the facility has demonstrated successful black liquor concentration at the 500 gpm scale with monthly uptime as high as 96%.

Application: In this work, the authors describe the operation and performance of the world's first commercial scale membrane system for the concentration of black liquor. The data reported and accompanying analysis indicate that this technology offers significant financial and energy savings benefits to kraft and similar mills.

Chemical separations utilizing membranes are frequently considered for reducing the capital and energy requirements of concentration and purification steps in many industries. In particular, membrane separations such as reverse osmosis are up to 90% more energy efficient than thermal evaporation as they do not require a liquid to vapor phase transition [1]. Because more than 30% of the energy consumption of a kraft mill is consumed in black liquor evaporation [2], the pulp and paper industry has long awaited a membrane capable of withstanding the high temperatures and alkaline environments that weak black liquor presents. Both polymeric and ceramic membranes have been tested for service in black liquor concentration [3-5], with none reaching commercial scale adoption due to the high solids, pH, and temperature requirements.

Graphene oxide is an exciting new membrane material, capable of withstanding the pH, temperature, and high solids content of black liquor. Our team has previously reported on success at the pilot scale [6]. In this paper, we report on the first mill scale system for the concentration of black liquor, built by Via Separations at the International Paper Grande Prairie, AB, Canada, facility with the assistance of the mill team.

The Grande Prairie system not only presents an opportunity to quantify the benefits of a completely new approach to black liquor concentration, but it also provides a chance to learn from the first ever such installation and improve the design and materials for future systems. Emphasis is placed here on the impact on the overall mill energy balance and the benefits for typical North American mills.

While the evaporators are the largest steam user in the back end of the mill and because of the low cost of energy for many North America mills and high steam economy of many European mills, the primary economic benefits to adding a membrane system, or making any upgrades to an evaporator train, are often driven by chemical costs, reliability, or production needs rather than energy savings [7,8]. This is certainly the case for mills planning expansions or facing end-of-life issues, capacity limitations, or other challenges that would prompt them to consider a membrane system as part of an upgrade to the recovery process. The impact of the membrane system on washer optimization [7,9,10] is also calculated and indicates membrane systems will enable a shift to lower chemical consumption and higher dilution factor washing.

SYSTEM AND METHODOLOGY

The project at the Grande Prairie facility launched in April 2023 and broke ground in June 2023. Construction was completed in 11 months, with operations and commissioning taking place in May 2024. The system was online and operational starting on May 19, 2024. In addition to the core concentration system, the project team also installed tanks between each subsystem and fully enclosed the system within a new building. The membrane system itself is composed of subunits that can be laid out either adjacent or stacked vertically to reduce space in other designs. The membrane system was laid out to occupy approximately 50 ft x 55 ft within the building.

The Grande Prairie system is built to process a 500 gal/min slipstream of the mill's weak black liquor flow from the fiber line, as shown in **Fig. 1**. The system is designed to concentrate the weak black liquor while producing permeate that can be reused for brownstock washing in the same manner as non-steam effect evaporator condensate is treated.

Prior to being fed into the membrane system, the liquor is processed in a pretreatment unit. Pretreatment is designed to remove suspended solids that are primarily fibers. Overall, a very small portion of the total solids are concentrated here, and the fiber rich liquor can be introduced back to the mill in the most beneficial way for the site. The simplest possible integration — a combination of the fiber reject stream with concentrated liquor from the rest of the system — was used here. The defibered liquor is fed to the membrane system for concentration.

The membrane system utilizes multiple passes as shown in **Fig. 2**. The passes are formulated to process different aspects of the liquor, resulting in a more energy and capital efficient design by concentrating the largest molecules first and then passing the permeated intermediate to a tighter pore membrane for removal of smaller species. Thus, the first pass permeate becomes the feed for pass 2 and pass 2 permeate feeds pass 3, etc. This results in 79% of the membrane modules serving in pass 1 and cascading smaller passes and module counts in later passes (**Fig. 3**).

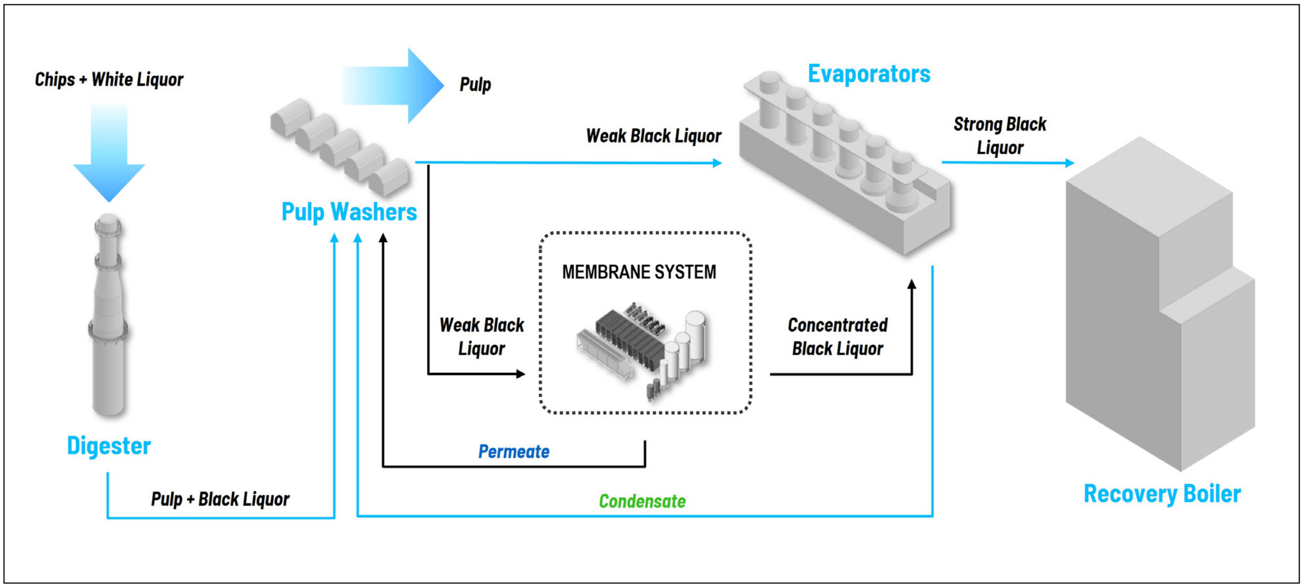
The two primary metrics used to quantify membrane performance in the membrane system are flux and permeate solids. Flux is defined as follows:

$$J = Q/A \tag{1}$$

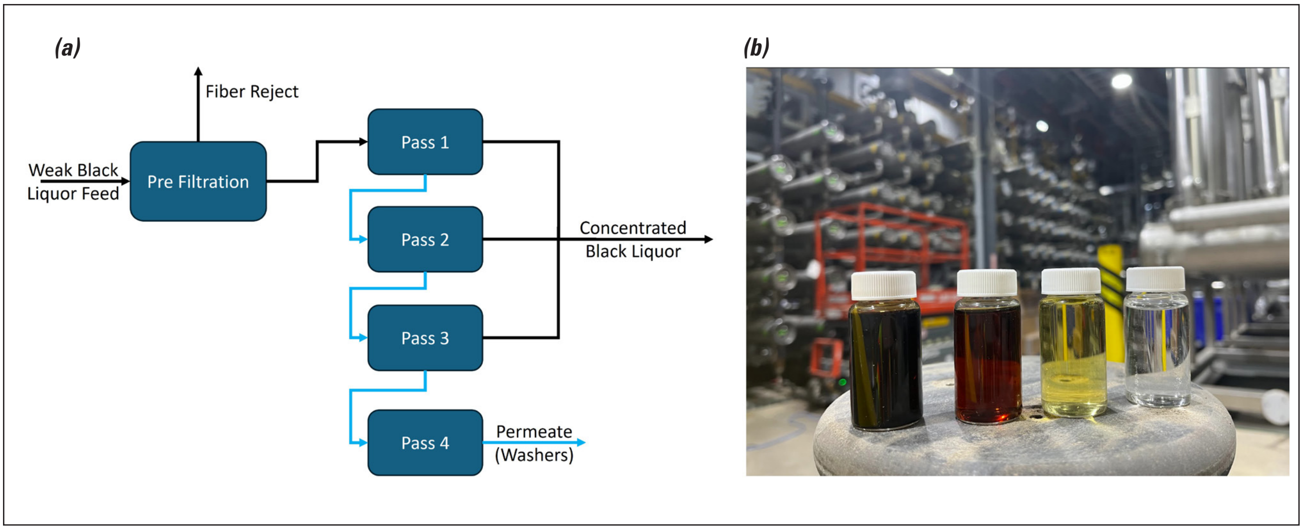
where J is the membrane flux in gallons per foot square per day (gal/ft^2/day); Q is the total volume going through a membrane in gal/day; and A is the membrane active area in square feet. Flux is important because it directly correlates with throughput. In general, flux is a membrane property, but process parameters like feed pressure, temperature, and solids content can affect it. For a required permeate production, less membrane area (or fewer modules) is required with a higher flux, which allows for lower capital costs (fewer membrane housings required to achieve specified system flowrates) and operational costs (fewer membranes to replace).

Permeate solids are a key parameter for graphene oxide membranes because the performance of downstream passes is dependent on the permeate quality of the pass before. For example, as pass 1 permeate solids decrease, pass 2 performance increases, and ultimately cascades to final system permeate production or quality increases.

Energy consumption is a primary driver of operating expenses for evaporators, membrane systems, and a pulp mill overall. Additionally, it is often of strategic, corporate, or public policy importance and an indicator of fundamen-



1. Via Separations membrane system integration into a mill process flow diagram. The system draws a slipstream of black liquor heading to the evaporators and returns a concentrated liquor stream as well as a clean water permeate for reuse in pulp washing.



2. (a) Process flow diagram of the membrane system. First, fibers are removed from the feed by a prefiltration unit before entering a four-pass concentration system with each pass of progressively smaller pore membranes processing the permeate from the pass until water of sufficient purity for use in the washers is produced. The concentrate system from each of the first three membrane units is combined and returned to the evaporator feed. The concentrate from the 4th pass is recycled to the pass 3 feed. (b) Samples of black liquor feed, pass 1 permeate, pass 2 permeate, and pass 4 permeate showing the progressive removal of colored species from the liquor.

tal efficiency. Comparing the energy intensity of evaporation and the membrane system, the power consumption required to produce a gallon of clean water was measured.

The system's power draw is primarily dominated by high-pressure pumps used to achieve the necessary flow rates and membrane operating pressures, but the total power draw including auxiliary equipment in the facility was considered. For both the evaporators and the membrane system, energy requirements for building functions such as control room heating and lighting were not included. Equation 2 gives the electrical energy required to drive the membrane process:

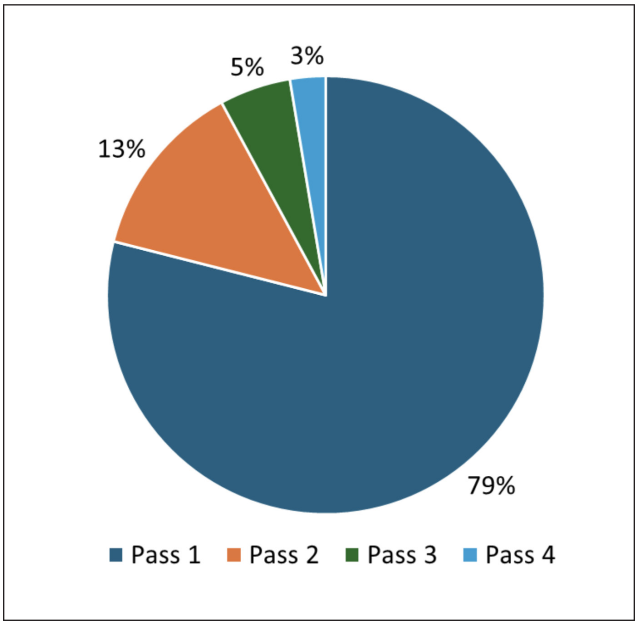
$$P_{mem} = \frac{P\,t}{W_{mill}} \qquad (2)$$

where P_{mem} is the power consumption for a membrane system per gallon of permeate (kWh/gal); P is the total system power consumption (kW) during a period of operation, t; and W_{mill} is the total amount of permeate returned to the mill during that period.

To determine the specific energy requirement for evaporation, a typical power boiler was considered to capture the impact of marginal increases or decreases in fuel consumption. We used Eq. 3, which considers both the energy required to generate steam from natural gas in a power boiler and the electrical power produced when that steam is converted from high to lower pressure:

$$P_{evap} = \frac{E}{S\,\eta} \times \frac{kWh}{3410\,BTU} - \frac{Y}{S} \qquad (3)$$

where P_{evap} is the net energy requirement to drive evaporation; E is the enthalpy difference between high pressure steam leaving the power boiler and feed water to that boiler; S is the evaporator steam economy; η is the efficiency of the boiler; and Y is the turbine yield for the back pressure turbine used to convert between high pressure and evaporator steam, expressed in kWh/lb of steam. Using the density of clean water, P_{evap} can be converted between units of kWh/lb and kWh/gal to compare directly to P_{mem}. The



3. Module distribution of the different membrane passes utilized in the Grande Prairie design. As the permeate is processed and larger molecules are removed, the sizing of the later passes decreases, meaning the first pass represents 79% of the system.

Parameter	Value	Unit
Baseline steam economy	4.1	
State-of-the-art 7-effect steam economy	5.95	
Natural gas power boiler efficiency	80%	LHV %
Natural gas price	5.00	$US/MMBtu
Turbine efficiency (backpressure)	8.00	metric ton steam/MWh
Electrical power cost	45	$US/MWh
High pressure steam, enthalpy change	1225	BTU/lb
Washer filtrate solids	5.5%	TDS
Initial evaporator feed solids	17%	TDS
Sodium concentration of liquor	700	lb Na_2O/a.d. metric ton
Consistency of pulp at washer inlet	27%	
Consistency of pulp at washer outlet	33%	
Baseline sodium recovery (washing yield)	94%	
Days of operation per year	350	days
Liquor makeup cost	900	$US/ton Na_2O
Bleaching chemical cost	1800	$US/ton ClO_2
LHV: lower heating value; MMBtu: 1 million British thermal units; TDS: total dissolved solids; Na_2O: sodium oxide; ClO_2: chlorine dioxide.		

I. Key assumptions chosen for modeling of evaporators and associated mill operations. Typical values for pulp mills in North America were used to provide comparison to a membrane system.

assumed energy density and other key assumptions can be found in **Table I**.

To estimate the impacts of the membrane system on the optimal dilution factor, we followed the methodology commonly used in the literature [7,9,10], including the correct conversion from 2.63 lb of active chlorine to 1 lb of chlorine dioxide (ClO_2). Briefly, the washers are modeled for changes in dilution factor by assuming a fixed Norden efficiency. Increased dilution factor lowers carryover of liquor species into the washed pulp but increases the energy required for black liquor concentration – either that of an evaporator or a membrane system. Note that in the case of a new membrane and legacy evaporator combination system, the membrane system receives all the additional wash water from the increased dilution factor to avoid adding load to the evaporators, and the membrane system power consumption is used for this marginal wash water.

Any black liquor evaporator or membrane installation decision requires consideration of both the capital and operating costs. To estimate evaporator costs, Cantrell's analysis [8] of evaporator upgrade costs was used and corrected to 2023 data using the Chemical Engineering Plant Cost Index (CEPCI). Because this data provides evaporator equipment cost only as a function of capacity, it may overestimate the cost of evaporator systems with fewer effects or underestimate the costs of more efficient systems.

The cost of a membrane-based evaporator system was determined using the equipment costs used or quoted for this project. To generate the most applicable results for mills considering the technology, a second-generation design was developed by incorporating the learnings described in this work. For consistency, the same 4.0 Lang factor used by Cantrell and representative of typical projects was used for both membrane and evaporator capital cost estimates.

To compare systems with different relative capital and operating costs, the total levelized cost was used. The levelized cost is the net present costs divided by the total amount of water evaporated or permeated over the project life. The clean water flows are also discounted to a present value using the same interest rate as the costs, as shown in Eq. 4:

$$Levelized\ Cost = \frac{\sum_y \frac{C}{(1+i)^y}}{\sum_y \frac{W}{(1+i)^y}} \tag{4}$$

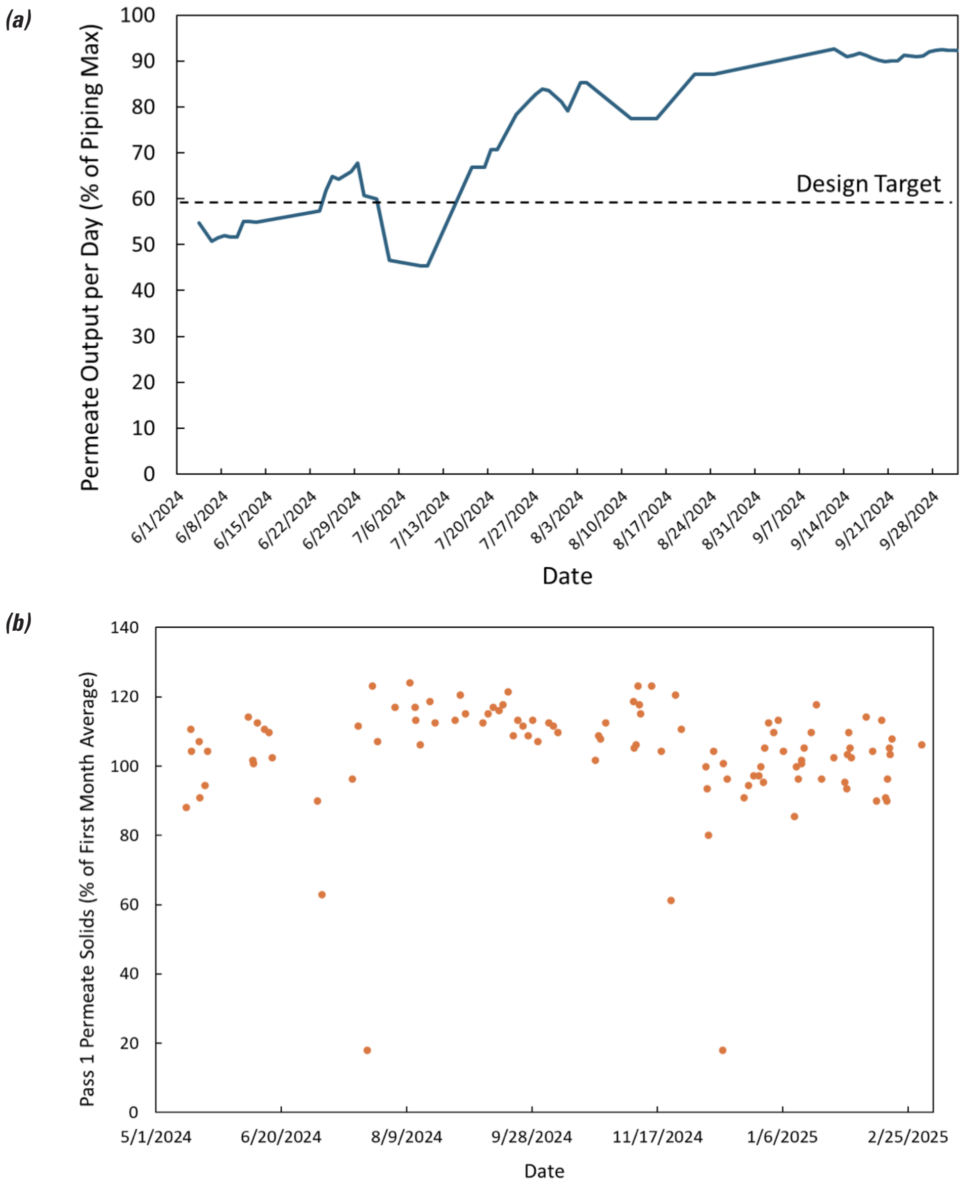
where C is the capital or operating that occurs in year y; W is the permeate or condensate flow produced by the equipment in year y; and i is the interest rate used. Based on the authors' discussions with pulp mills, a two-year fabrication, installation, and commissioning period was used for the evaporator system. The design, construction, and delivery of this project was completed in 13 months, so a one-year duration was used for the membrane system for simplicity. A 15-year project lifecycle and 10% interest rate were assumed for all projects.

RESULTS AND DISCUSSION

Membrane performance

In the membrane system, the first pass modules see the most challenging chemical environment, as the feed is the most concentrated there. Previously reported work focused on developing and demonstrating fouling resistance and effective cleaning strategies for this pass [6].

As shown in **Fig. 4**, operation at scale and further op-



4. (a) Permeate output of a set of 108 graphene oxide modules in pass 1 for a period of initial optimization. Values have been normalized to maximum levels allowed for minimizing piping erosion due to the diameter of the permeate piping and high fluid velocity. As more has been learned about the operation of the system, throughput has increased, exceeding the design target by 53% – despite module aging – and demonstrating that future systems could operate with fewer modules. (b) Permeate solids through the same set of graphene oxide membranes. As the system was initially optimized, throughput was favored over consistent permeate solids levels. Continuing operation indicated that the system would perform better with lower permeate solids, leading to the tuning of process variables such as pressure and temperature to decrease permeate solids, without sacrificing throughput.

	August 2024	February 2025
Number of pass 1 module cleanings	20	2

II. Table comparing uptime and pass 1 module cleanings for two months in the first year of operation. As membrane operating conditions were optimized, 90% fewer cleanings were necessary.

timization has resulted in pass 1 modules that have significantly overperformed the design throughput by more than 50%, with consistent performance over time. In fact, flux performance has been constrained by permeate pipe diameter and potential pipe erosion due to high fluid velocities in the permeate piping. Figure 4a is normalized to this maximum flow rate, and the original design point is marked at 59% of maximum flow. This operational experience at scale is beneficial to future system design and construction work, as a higher-than-expected membrane flux correlates to both lower capital and operating costs. Additionally, performance has been demonstrated to be robust over time, allowing for fewer modules required to maintain production.

In addition to producing expected flow rates of permeate, generating appropriate concentrations of permeated species from each pass is critical to performance of the subsequent pass and ultimately the cleanliness of the final water produced. Similar to membrane flux, permeate solids concentrations have been consistent over time, as shown in Fig. 4b, with no sudden or gradual increases in permeate solids. This indicates that graphene oxide module performance is stable, both in terms of throughput and permeate quality. Together with steady flux, low permeate solids are the key indicator for determining membrane life, with the modules in Fig. 4b passing one year in operation at the time of publication.

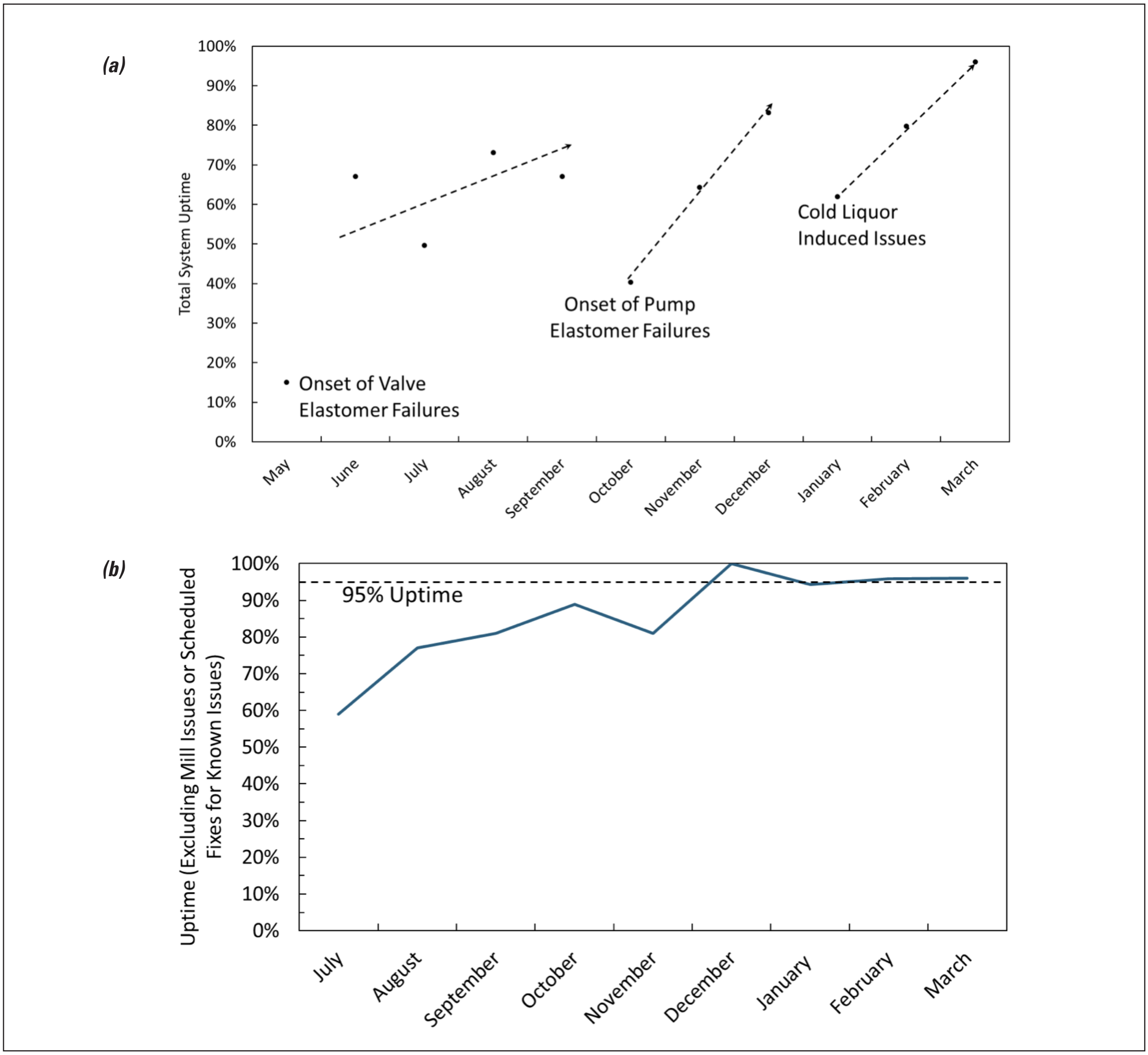
Additional learnings contributed to the understanding of how future systems can be better designed. One significant improvement that was identified is the decrease in necessary cleaning frequency of the graphene oxide membranes, as seen in **Table II**. This cleaning takes roughly 30–60 min and is performed on a subset of the modules at a time to prevent overall system downtime. Most cleans are performed using permeates generated within the system, and any added chemicals are compatible with the liquor cycle. After use, all clean-in-place (CIP) wash fluids — circulated to clean membranes without disassembly — are returned to the feed tank to prevent additional load on water treatment. In previous pilot studies [6], membranes were cleaned daily. However, in the optimization of this system, it was determined that graphene oxide membranes can operate up to 10 times longer between cleanings. This decrease in cleaning frequency leads to an increase in pass 1 time at full capacity, and a decrease in permeate used to clean membranes instead of being sent to the washers. It is hypothesized that the decrease in required cleaning frequency and increase in module flux are due to improvements in prefiltration technology utilized in the system vs. previously piloted modules. This reduction in membrane cleaning frequency enables greater uptime, reduced operating expenses from cleaning, and a more consistent and stable system operating window.

System reliability

System startups always present operational challenges. As a first-ever membrane concentration system for black liquor, learnings and challenges were expected. With the benefit of nearly one year of operation, a holistic look at learnings and progress is now possible. One area of particular focus was the overall system uptime. The largest source of downtime was material compatibility issues in the pumps and valves. Initial operation revealed that valve seats and pump seals used in previous pilot systems and multiple parts of this design were not compatible with this combination of temperature, liquor chemistry, and increased contact time. This incompatibility caused premature elastic component failure over the course of weeks instead of years. Over ten months, more than 100 valve seats were replaced (mostly in the prefiltration process area), and 17 pumps had seals changed, sometimes multiple times. These frequent valve and seal failures contributed to the downtime of the system. No failures have occurred in the upgraded materials, indicating the problem has been resolved.

As suitable materials of construction were identified for the valve seats and pump seals, uptime has increased, as shown in **Fig. 5**. An additional significant contributor to downtime in winter months was the performance of the prefiltration unit, which had not been piloted previously. Operation revealed that process upsets have significant impacts on prefiltration throughput. These decreases in throughput were precipitated by sudden changes in the temperature of the prefiltration unit caused by variations in black liquor feed temperature. These temperature changes caused the prefiltration unit to foul, which would prevent operation while the unit was cleaned. The process conditions contributing to decreased prefiltration throughput were identified, and automation was implemented to avoid sudden swings in temperature without slowing production. As material compatibility and prefiltration throughput issues were addressed, uptime has become more consistent and reached 96% in the last month before this publication.

To illustrate the reliability trend while known issues were being resolved, Fig. 5b provides uptime, excluding hours of mill downtime and scheduled resolutions to known issues. This uptime trend shows a rapid improvement from 59% in July 2024 to an average of 97% from December 2024 through March 2025. This highlights the gains in system reliability and expected operational reliability with this system going forward.

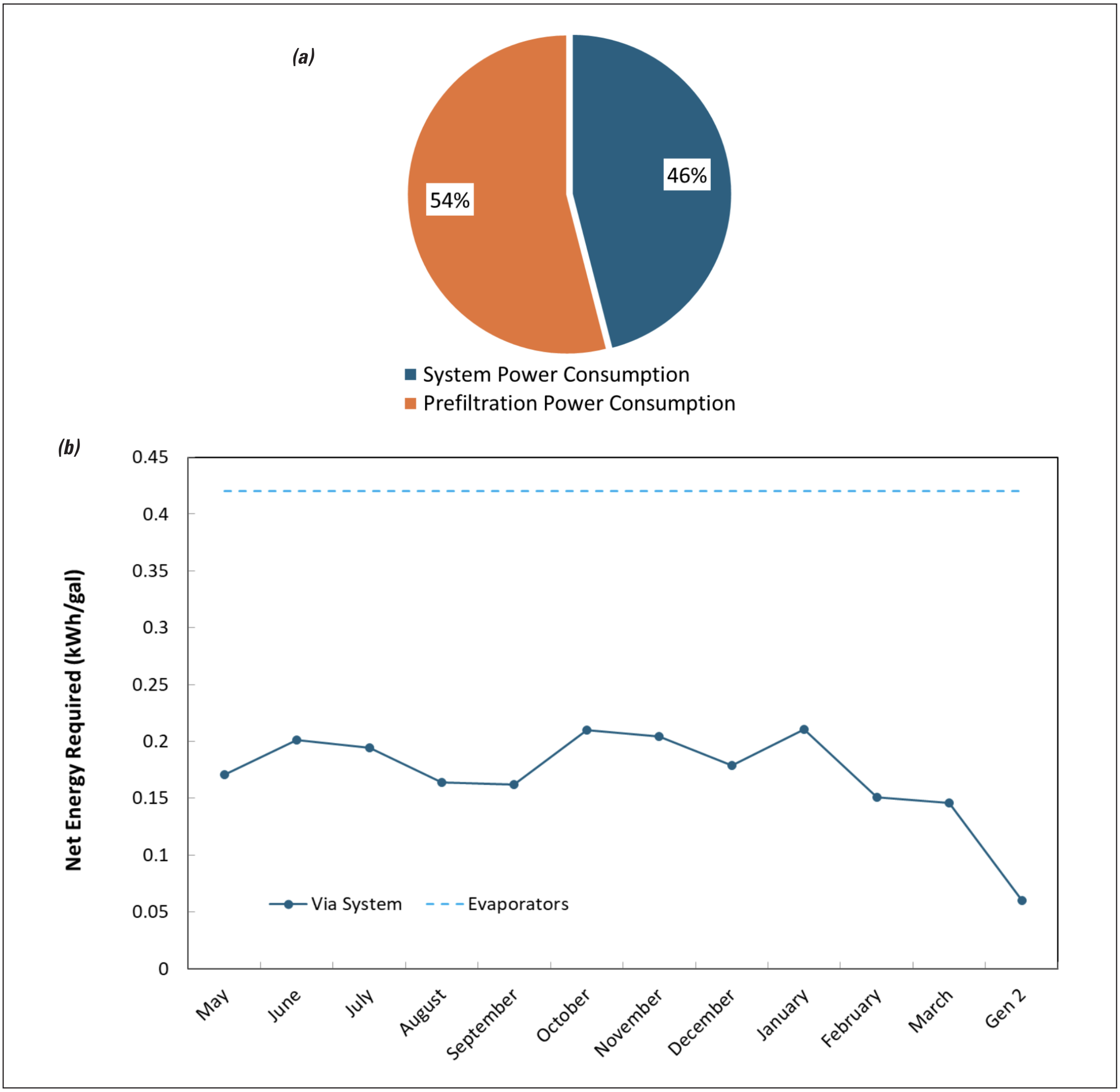


5. (a) System uptime since startup inclusive of all downtime sources: mill downtime, unexpected issues, and stops to resolve known issues. Learnings and sources of downtime have followed three distinct cycles, with the first two precipitated by failures in elastomer materials and the last requiring updated controls to navigate slugs of cold liquor. All three issues were successfully identified and ultimately addressed, resulting in monthly uptime exceeding 95%. (b) Uptime excluding hours caused by mill issues or scheduled maintenance events to resolve known issues. For future months, total uptime is expected to remain close to this figure, plus any downtime required by overall mill downtime.

Energy efficiency

The world's first full-scale, membrane-based black liquor concentration system allows for complete proof of the energy efficiency of the process at scale and opens significant opportunities to further improve the energy efficiency of this approach. By integrating a membrane system upstream of the evaporators, mills can enhance overall energy efficiency by reducing the evaporator load, thereby lowering steam and fuel requirements. This section reviews the already significant reduction in energy intensity for removing water from black liquor and looks ahead to opportunities to further reduce the energy requirement of liquor concentration for this and other systems. To accomplish this, optimal values for process variables were established via system operation. This includes temperatures, pressures, and fluid velocities for every single pass in the system after initial commissioning.

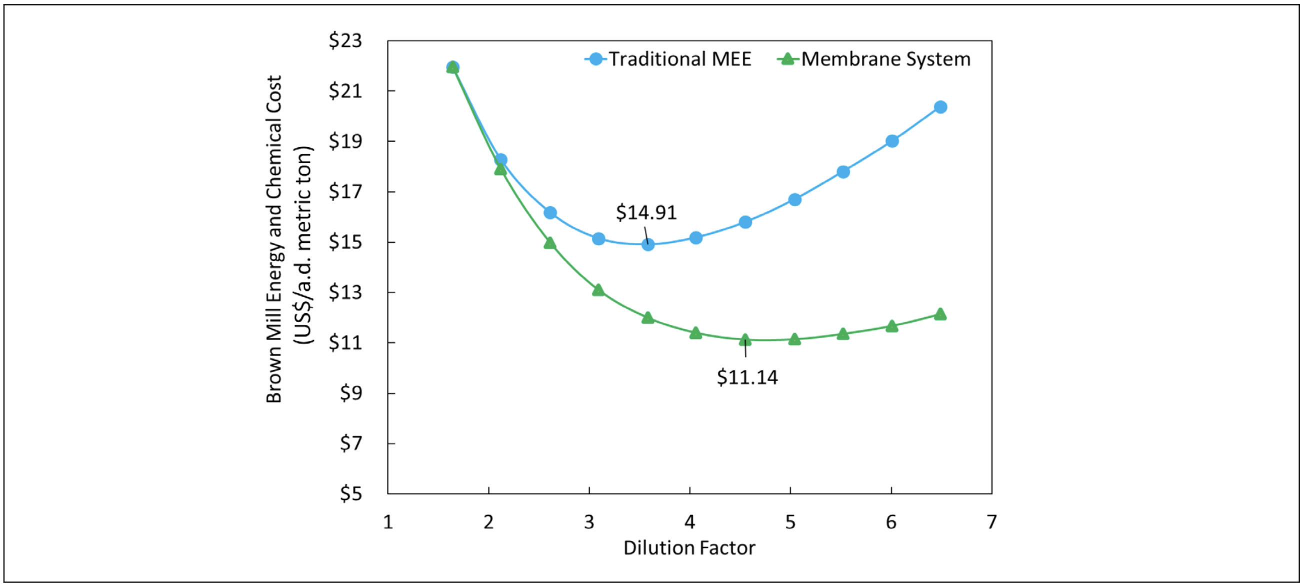
Figure 6a highlights a breakdown of power consumption. The energy savings arise from the fact that membrane separation does not rely on phase-change, but instead leverages pressure-driven filtration to extract clean water at a fraction of the energy input. The largest contributor to



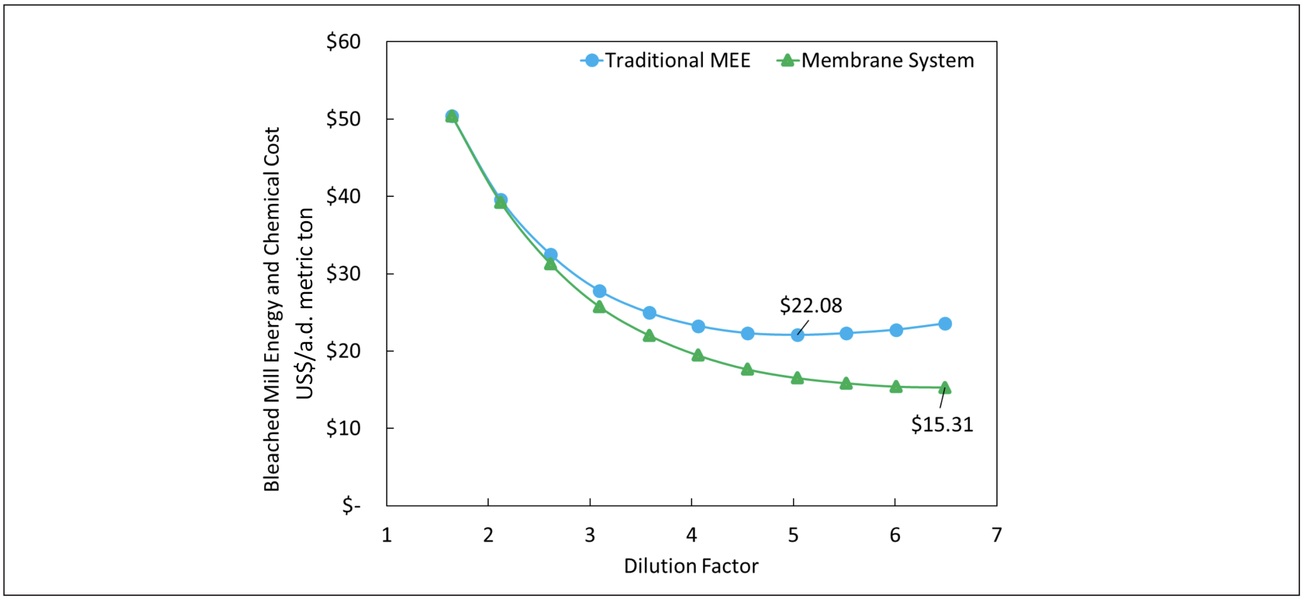
6. (a) Breakdown of the power consumption of the system showing pretreatment and all other sources. As the pretreatment system has been eliminated from future designs and does not concentrate liquor, it is not included in system energy calculations. (b) Energy required by the membrane system per gallon of permeate in comparison to a typical evaporator per gallon of condensate. The membrane system demonstrated a 60% reduction upon startup with subsequent optimization and updated designs (Gen 2) reaching an 86% reduction in energy required.

the system's power consumption is the prefiltration unit that removes fibers from liquor. This component alone accounts for 54% of the total system's power draw, despite not contributing significantly to liquor concentration, making prefiltration a target for optimization. Other simultaneous field deployments by our team have demonstrated the ability to eliminate this unit. Since this portion of the unit is not applicable to future designs and does not contribute to the concentration of the liquor, it has been omitted from the comparison to a multiple-effect evaporator.

To contextualize the energy efficiency of the membrane system, we compare it directly to a multiple-effect evaporator. As shown in Fig. 6b, the system had an initial power consumption of 0.17 kWh/gal, which improved through optimization to 0.15 kWh/gal, or 65% less than required for a typical multiple effect evaporator inclusive of cogenerated power. The assumed multiple effect evaporator (**Table I**) requires 0.55 kWh/gal of thermal energy and generates 0.13 kWh/gal of power for a net requirement of 0.42 kWh/gal. The higher relative price of electricity to natural gas or other thermal fuels is only partially



7. Total cost of operation analysis of a brown mill washing system deploying either a multiple effect evaporation (MEE; blue) or membrane based (green) system for additional liquor concentration. Introduction of a membrane system to handle increases in shower water produces a US$3.8/a.d. metric ton reduction (25%) in net energy and chemical costs and increases the optimal dilution factor by 1.0.



8. Total cost of operation analysis of a bleached mill washing system deploying either a multiple effect evaporation (MEE, blue) or membrane based (green) system for additional liquor concentration. Introduction of a membrane system to handle increases in shower water produces a US$6.8/a.d. metric ton reduction (31%) in total energy and chemical costs and increases the optimal dilution factor by 1.5.

mitigatory of the large efficiency gap between evaporators and membrane systems, and while not considered in the energy analysis, it is included in the cost analysis in the "Capital and operating cost analysis" section.

Based on data from this project and other field demonstrations, we have developed a second-generation design that eliminates surplus capacity in areas where the system exceeded expectations and only requires 0.06 kWh/gal of permeate. This represents an efficiency improvement of approximately 86% over the conventional evaporator.

Impact on pulp washing

Reducing chemical consumption outranks reducing energy consumption as a priority at many mills. In this section, we consider the impact of introducing the Via Separations membrane system to washer optimization calculations. We report that the system demonstrated the ability to operate at lower energy intensities, fundamentally shifting the historical optimization curves. Both a brown and bleached pulp mill are shown in **Fig. 7** and **Fig. 8**. The introduction of a membrane system increases the optimal dilution factor by 1 for the brown mill and 1.5 for the bleached mill. This creates a 25% and 31% reduction in total chemical costs for the brown and bleached mills, respectively.

It is important to note that this analysis assumes the mill is already operating at the optimal dilution factor. Due to evaporator limitations, many mills are not able to hit their optimal dilution. In such a scenario, Fig. 7 and Fig. 8 illustrate how the potential chemicals savings from investing in additional membrane or evaporator capacity could provide a further two or three times multiple on the savings discussed here.

Washing optimization curves were generated assuming there are no hydraulic limitations on the removal of wash water from the filtrate system. Additionally, capital and maintenance costs are not typically considered in this analysis [7,9,10], and thus the cost curves should be used to determine the optimal point for washing if the mill already has available evaporator or membrane system capacity. Alternatively for new systems, the benefits of increased washing should be weighed against these excluded costs as in the "Capital and operating cost analysis" section or in a typical return on investment calculation for the project.

Each mill and system will have a unique washing optimization curve. The curve will be impacted by chemical prices, fiber source, kappa, washing equipment, fuel prices, and evaporator efficiency (Table I). While each mill's curve is unique, the shape should be consistent. Each mill should see a shift "down and to the right" towards a higher dilution factor with the addition of a membrane separation system due to the demonstrated reduction in energy costs.

As mills push for continuous improvement and optimization, the impact of wash water and recovery is often a primary objective. The balance is highly dynamic, being influenced heavily by the chemical and energy prices the mill is experiencing. As energy prices decrease, the mill can pursue additional chemical recovery to decrease the total cost of operation. If energy prices increase, the mill can maximize fuel savings and increase chemical use back to prior levels. It is beneficial for mills to not only understand their current state but also understand how shifting prices could impact the balance to maximize benefits from a membrane system by leveraging different benefits in response to changing economic factors.

Capital and operating cost analysis

As discussed previously, the membrane-based black liquor concentration system has demonstrated reductions in the energy required to concentrate black liquor, saving both chemicals and energy. This project has also generated learnings in system design, materials of construction, efficiency, reliability, and overall equipment costs, lowering the total installed cost for updated designs.

Table III presents a summary of the capital and operating expenses for a mill making a capital purchase to replace or install new evaporator capacity. For the same capacity, the second-generation design represents a 43%

	Baseline Evaporators	7 Effect Evaporators		Membrane System	
	Value	Value	Reduction	Value	Reduction
Total equipment cost	11,820,741	$11,820,741	0%	$6,788,642	43%
Total installed cost	$47,282,963	$47,282,963	0%	$27,154,569	43%
Steam economy	4.10	5.95		N/A	
Annual fuel costs	$4,991,623	$3,439,605		$0	
Power consumption	(4.85) MW	(3.34) MW		2.30 MW	
Annual maintenance and membrane replacement	$200,000	$200,000		$2,100,000	
Annual cost of power	$(1,833,657)	$(1,263,529)		$869,551	
Total annual operating expenses	$3,357,965	$2,376,077	41%	$2,969,551	12%
Total present cost	$67,636,375	$60,846,992	10%	$51,841,212	23%
Levelized cost per ton	$7.32	$6.58	10%	$5.10	30%

III. Comparison of a mill capital purchase for increasing the capacity of an evaporation system by 640 gal/min of condensate or permeate. Currency values are in 2023 US$, and an assumed energy cost of 45 $US/MWh was used. A baseline case with a steam economy of 4.1 is compared to both a 5.95 steam economy system (7 effect evaporators) and a membrane system based on the project reported in this work. The membrane system offers significant reductions in capital cost compared to data available for adding new evaporator capacity, and operating costs savings are strongly dependent on the steam economy of the evaporators. For a 15-year project life, capital costs were found to be significantly more important than operating costs. The total cost was lowest for the membrane system by US$2.21/ton of water removed over the project life (30% reduction).

reduction in the capital cost required to deliver a project, a savings of US$20.1 M compared to investing in an equivalent evaporator installation.

In determining the operating costs, a steam economy of 4.1 was used for a baseline case to represent a typical North American mill. To represent the state-of-the-art case for new evaporator builds with high efficiency, a steam economy of 5.95 was used [8]. For the system detailed in Table I, the membrane system reduces operating expenses by 12% over the baseline evaporator option. Because the membrane system adds new operating costs for membrane modules and electrical power, the 5.95 steam economy saves 41% over the baseline.

While the membrane system is lower capital and operating costs than a 4.1 steam economy set and thus more financially attractive, to assess the tradeoff between operating and capital costs for the 5.95 economy set, a levelized cost is used to compare the total cost of ownership over a 15-year project life. Due to the lower operating costs, the more efficient evaporator system has a 10% lower levelized cost of water removal (US$6.6/ton) vs. the baseline evaporator system (US$7.3/ton), which is consistent with our observation that modern mills install systems of steam economy greater than 5.0 (although typically less than 5.7). However, due to the US$20.1 M in capital cost savings, the membrane system allows for a 30% reduction in levelized cost over the baseline to a final levelized cost of US$5.1/ton, making the membrane system design the most cost-effective method for concentrating black liquor. Ultimately, the project return will vary depending on the needs of the mill and the associated savings and revenue. When incorporating chemical savings, energy savings, and any applicable expansions or avoided downtime, a rate of return of 30% was calculated.

CONCLUSIONS

The first-of-a-kind membrane project has demonstrated a 65% reduction in energy required to remove water from black liquor. The system has made steady improvements in reliability and reached 96% monthly uptime. These advances were enabled by several learnings and improvements to the system, many of which were identified in the first few months of operation. Washer optimization calculations determined a 25% and 31% reduction in chemical and energy costs for a brown and bleached mill, respectively. We estimated a further US$20 M capital cost savings relative to an evaporator expansion project and an overall 30% reduction in the levelized cost to concentrate black liquor. **TJ**

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ABOUT THE AUTHORS

When we started Via Separations, our vision was to transition unit operations where evaporation or distillation are the available tools for concentration or purification. Our early interactions with pulp mills quickly taught us that not only were they often entrepreneurial in nature, but black liquor concentration was a major part of mill energy balances and many capital upgrade projects. As we found mills who were excited to pilot our technology as soon as it was available, we focused our efforts on serving this industry. The collaborative, no-nonsense Grande Prairie mill and broader International Paper team is a perfect example of why it quickly became clear that this topic was the area to focus our efforts for years to come.

We have previously published models of the impact of membrane processes on black liquor evaporation and the results of piloting the technology. Now, with our fourth publication in the current issue of *TAPPI Journal*, we are excited to report on the deployment of a full-scale system.

This work has been a significant undertaking involving many people at Via Separations and our partner organizations over the last eight years. The most difficult challenge has been bringing the right people together to anticipate the challenges at each point in scaling up 10 million times from the postage stamp materials we started the business with to the more than football field of membrane area used in this project.

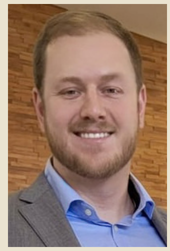
Through this project, we learned a lot about how to quickly and effectively deliver projects at scale. The lessons learned list is hundreds of items long, ranging from little things about sample station design to big ones about how to structure communication between different teams working together.

From a certain perspective, the most surprising thing is that the technology works so well. There were lots of unknowns and things not yet proven when we first started this company or even this project. Certainly, plenty of people with a lot of experience in this industry had a healthy skepticism, even if they were rooting for us.

The results of this project clearly show that under typical conditions, mills should use a membrane-based process for concentrating their liquor before feeding either an existing or a new evaporator train. It uses less energy than typical evaporators and much less capital cost than even state-of-the-art builds. Now that we have done it at scale, there isn't much room to come up with reasons not to utilize it in future upgrades or to address operational issues today.


Goffinet


Mason


Kraft


Harris


Kitch-Peck


O'Malley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Rivera


Pillay


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Caron


MacDonald


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