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Resource and Pathways Analysis for Decarbonizing the Pulp and Paper Sector in Quebec

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ABSTRACT

Decarbonizing industries could significantly increase electricity demand, necessitating strategic grid expansion. This study evaluates the impact of decarbonizing the Pulp and Paper Sector under four 2050 scenarios: carbon capture, biomass-based, direct electrification, and indirect electrification. A bottom-up approach is employed to estimate 2020 final energy demand by heat grade and subsector. Both final and primary energy demand systems are modeled, accounting for the efficiencies of end-use technologies and primary energy transformation processes. The analysis compares primary renewable energy demand (electricity and biomass) normalized per ton of equivalent CO_2 avoided against a business-as-usual scenario. It also considers the requirements for wood residues, organic waste, and CO_2 storage. The carbon capture scenario, while low in electricity demand, requires significant organic waste for renewable natural gas production and 2.6 Mt of CO_2 storage to offset direct and indirect emissions, making it the least feasible due to uncertainties around carbon storage in Quebec. Among the remaining scenarios, the direct electrification stands out by offering the lowest primary energy demand. It combines heat pumps with electric boilers for steam production and lime kilns are converted to a plasma-based solution. The study also includes a sensitivity analysis highlighting the potential of energy efficiency measures to ease the burden of decarbonization.

Keywords: Decarbonization, Energy Conversion, Modelling and Simulations, Planning, Carbon Capture, Pulp and Paper

INTRODUCTION

Achieving net-zero emissions by 2050 will require significant adaptations in industries, increasing pressure on electric grids. Forecasting industrial energy demand is important for electric utilities and requires a deep understanding of each sector. In Quebec, Canada, the pulp and paper sector (PPS) may need to make major adjustments to reduce GHG emissions from fossil fuel combustion, which accounted for 12% of total industrial emissions in 2020. The PPS has several abatement solutions to choose from, including installing carbon capture units, shifting to sustainable natural gas, increasing biomass use, electrifying process heat, or using hydrogen for indirect electrification.

Besides these solutions, which can be combined, the PPS could further contribute to the energy transition. The chemical and semi-chemical pulp subsector emits significant biogenic CO_2 from the combustion of residual liquor and lime regeneration. This biogenic CO_2 could be used to produce synthetic fuels and/or generate negative emissions to offset unavoidable GHG emissions [1]. These pathways are known as Bioenergy with Carbon Capture and Utilization (BECCU) and Bioenergy with Carbon Capture and Storage (BECCS). The possibility of contributing to BECCU and BECCS, along with the existing biomass supply chain value and the fact that most of the sector's GHG emissions can be easily abated with existing solutions, the PPS is well-positioned to play a key role in decarbonization. Therefore, multiple decarbonization scenarios for the PPS should be evaluated, particularly regarding their impact on electric grids.

This study explores scenarios involving the adoption of different end-use technologies to achieve net-zero emissions by 2050. Key performance indicators assess the impact on the electric grid and biomass resources. The study aims to provide insights based on a bottom-up approach to guide electric system capacity expansion.

METHODOLOGY

The methodology relies on publicly reported GHG emissions data [2]. Using a bottom-up approach, the final energy demand for low, medium, and high-grade heat is estimated for 2020 for two subsectors: semi-chemical and chemical pulp mills, and other categories. Low-grade heat is required for pulp bleaching, medium-grade heat for washers and evaporators, and high-grade heat for lime kilns. To estimate the evolution of energy demand, a useful energy approach is employed in the Low Emissions Analysis Platform (LEAP), considering an annual growth rate of 1% and the efficiencies of current and alternative end-use technologies. Based on energy demand, the software estimates primary energy demand, considering transformation process efficiencies.

Scenarios

A business-as-usual (BAU) scenario serves as a baseline, with four simplified scenarios modelled using constant useful energy. The end-use technologies per subsector and heat grade are illustrated in Figure 1. The first scenario, the carbon capture (CC) scenario, involves minimal adaptation of end-use technologies, relying on carbon capture and storage to achieve net-zero. A blend of 20% renewable natural gas (RNG) and 80% natural gas replaces natural gas. RNG is produced from organic waste, including food, agricultural, livestock residues, landfill sites, and wastewater. Light fuel oil and heavy fuel oil are replaced with liquefied gas blend. The carbon capture units are directly installed as post-combustion equipment on boilers and lime kiln to offset emissions from burning natural gas.

The subsequent scenarios involve significant adaptations of end-use technologies, converting them to biomass-based, direct electrification, and/or indirect electrification technologies. For low- and medium-grade heat, heat pumps (HPs) and high-temperature heat pumps (HTHPs) are prioritized, as they can effectively upgrade waste heat to produce hot water and steam. The proportion of process heat that can be supplied by heat pumps depends on factors like location, timing, temperature and flow rate of both waste and process heat streams. Marina et al. [3] estimated that heat pumps could supply up to 69% of process heat below 200°C in European PPS, though excluding (Semi-) Chemical Pulp Mills. For the entire sector, up to 65% is set for low- and medium-grade heat. Since recovery boilers already provide steam, HTHPs supply 45% of medium-grade heat in (Semi-) Chemical Pulp Mills. A sensitivity analysis complements the results to account for uncertainties. For the biomass-based (BIO) scenario, efficient bark boilers supply the remaining heat, with enhanced efficiency from crushing and drying processes using low-grade waste heat. For the direct (DE) and indirect (IE) electrification scenarios, electric boilers provide the remaining heat. For high-grade heat, a gasified biomass lime kiln is selected in the BIO scenario, though alternatives like torrefied biomass, pulverized wood or lignin exist [4], with gasified biomass being widely adopted in Finland [1]. For the DE scenario, an electrified plasma calcination process is selected [5], and for the IE scenario, a hydrogen-fired lime kiln is selected. Finally, while adoption of end-use technologies is not constrained by regional electric capacities, but wood residues are limited to current availability.

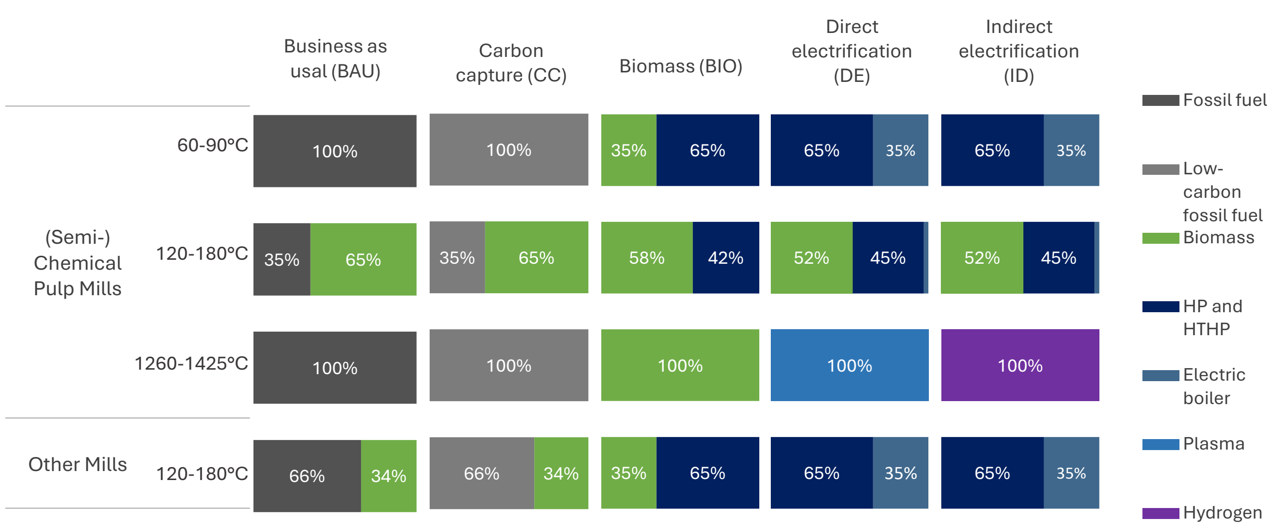

Figure 1: Useful energy distribution per scenario in 2050. **Fossil fuel** is a mix of natural gas, light fuel oil and heavy fuel oil. **Low-carbon fossil fuel** is a mix of natural gas, renewable natural gas and liquified natural gas blend. **Biomass** is a mix of residual liquor, wood bark and decentralized biogas. **HP, HTHP** and **EB** refer to heat pump, high temperature heat pump, and electric boiler.

Final energy demand

The final energy demand system includes both current and alternative end-use technologies. For low and medium-grade heat, current technologies are fossil fuel-fired, bark, and recovery boilers, while alternatives include efficient bark boilers, electric boilers, HPs, and HTHPs. For high-grade heat, the current technology is a fossil fuel lime kiln, while alternatives include gasified biomass, plasma-based solution, and hydrogen. Efficiencies and auxiliary energy requirements are listed in Table 1, using a low heating value (LHV) of 19 MJ/kg for wood residues. The final energy demand system also includes carbon capture technology, with an efficiency of 95% and energy requirements of 333 kWh_{el}/t for capture and conditioning with a membrane separation technology Zanco et al. [6]. This simplified approach may differ for lime kilns due to variations in CO_2 concentration and scale [7, 8].

Direct emissions are estimated by LEAP, following the IPCC AR5. Quebec's electricity grid, mainly powered by renewables, has a GHG emissions intensity of about 0.3% of Europe's average in 2023 [9, 10]. Emissions from imported non-renewable electricity are small, but by 2050, all imports are assumed to be 100% renewable.

Table 1: End-use technologies parameters

End-use technology	Efficiency	Auxiliary energy requirements
Low and medium-grade heat		
Boiler		
Fossil fuel	75%[11]	N/A
Bark	70%[11]	N/A
Recovery	65% [12, 13]	N/A
Bark (efficient)	80% [14]	Crushing: 32 kWh_{el}/t[1]
Electric	99%[11]	N/A
Heat pump		
HP	300%[3]	N/A
HTHP	250%[3, 15]	N/A
High-grade heat		
Lime kiln		
Fossil fuel	53%[16]	N/A
Gasified biomass	41%[4]	Drying: 465 kWh_{th}/t[4] Grinding: 278 kWh_{el}/t[4]
Hydrogen	56%[4]	N/A
Plasma-based	55%[16]	N/A

[1]Electric consumption of a bark crusher per dry ton of pine wood residues, based on vendor data.

Primary energy demand

The primary energy demand system includes centralized energy solutions such as natural gas, gas blend with RNG, liquefied gas blend, 100% renewable electricity, and green hydrogen. For the liquefied gas blend, energy for liquefaction, truck transport, and fugitive emissions are neglected due to data limitations, though it represents only 2% of final energy demand in the CC scenario. Green hydrogen is produced using alkaline electrolysers, with liquefaction and transport by trucks for storage and distribution. Decentralized energy solutions like wood residues, residual liquor, biogas from wastewater streams, are also included. Transformation processes and distribution efficiencies as well as fugitive GHG emissions are listed in Table 2. Fugitive emissions for natural gas are relatively low and have been estimated at 0.93%(vol.) by the CIRAIG [17], while those for RNG are considered negligible. The primary energy demand system also includes direct air capture technology, with an energy requirement of 2514 kWh_{el}/t [18], to offset the fugitive emissions of natural gas.

Table 2: Transformation processes and distribution parameters

Energy produced	Requirements	Primary energy
Green hydrogen	1.37 kWh_{in}/kWh_{out} [19]	Renewable electricity
RNG[1]	1.47 kWh_{in}/kWh_{out}	Organic waste
	0.05 kWh_{in}/kWh_{out}	Renewable electricity
Energy distributed	**Efficiency**	**GHG emissions**
Renewable electricity	93%[20]	-
Natural gas	96%[17, 21]	13.5 $g_{CO2eq}/MJ_{consumed}$[17]
Green hydrogen	95%[22]	11.6 $g_{CO2eq}/g_{H2leaking}$[23]
Natural gas blend	96%[17, 21]	10.8 $g_{CO2eq}/MJ_{consumed}$[17]

[1]The organic waste requirements are based on a theoretical assessment, assuming 50% average carbon content, a LHV of 5.55 kWh/kg, and a carbon conversion fraction of 0.85. The electricity requirement was estimated at 5% of the product's LHV.

Key performance indicators

Resource indicators, along with the reduction of GHG emissions, differences in biomass demand and CO_2 storage requirements, are calculated for each scenario. The GHG Performance Indicator (GPI) assesses the marginal renewable energy - electricity, biomass, or both - required per ton of GHG emissions avoided, as expressed in Equation 1. This indicator is evaluated by heat grade, subsector, and globally, relative to the BAU scenario.

$$GPI_i = \frac{E_i - E_{i,baseline}}{GHG_{baseline} - GHG}, \quad (1)$$

where E is the primary energy demand in MWh, GHG is the 100-year GWP emissions in ton of equivalent CO_2, i is the resource of interest (electricity, biomass or total).

RESULTS AND DISCUSION

The sector's thermal energy consumption in 2020 is estimated at 23 TWh_{th}, and its distribution by usage is illustrated in Figure 2.

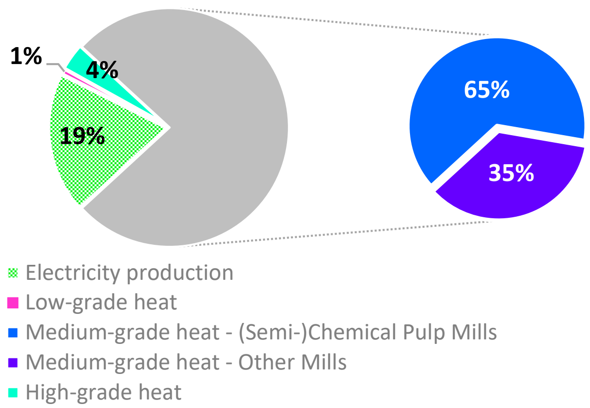

Figure 2. Distribution of the thermal energy consumption by usage.

Most consumption is attributed to steam used in various processes, with the remainder used for low- and high-grade heat in processes and on-site electricity production. The main fuels consumed in the (Semi-) Chemical Pulp Mills are residual liquor (63%), natural gas (25%), and wood residues (9%). For the Other Mills, the main fuels are natural gas (52%) and wood residues (37%). The use of gas directly fired in Through Air Dryers is neglected, slightly overestimating steam consumption. It is assumed that electricity production is fueled by wood residues and residual liquor.

Resource analysis

Figure 3 illustrates the marginal primary energy demand for each scenario and its breakdown by source. All scenarios achieve a 98-99% reduction in 100-year GWP direct emissions and a 96-100% reduction in indirect emissions. Residual GHG emissions result from the combustion of large amounts of biomass - wood residues and residual liquor – emitting biogenic methane and nitrous oxide. Only the CC scenario requires CO_2 storage, with 2.2 Mt to offset direct emissions and 0.4 Mt for indirect emissions.

The CC scenario requires more energy due to electricity needed by the carbon capture technology and RNG production, along with about 3.2 TWh of organic waste for RNG production. The other scenarios are fossil-free and more efficient than the baseline, but they required additional electricity, mainly for direct electrification. The DE and IE scenarios, the adoption of direct electrification technologies releases 4.7 TWh of wood residues that were used in bark boilers. Lastly, the IE scenario requires an additional 0.6 TWh for electrolysis to supply five lime kilns.

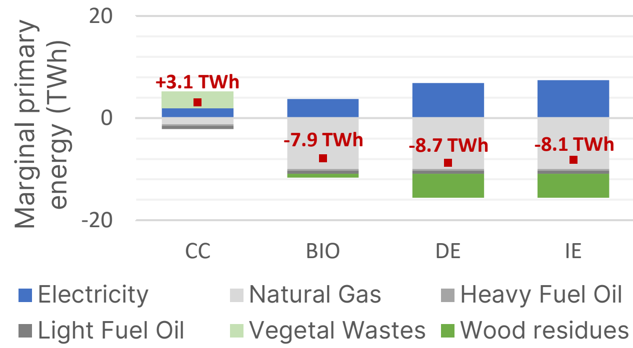

Figure 3. Marginal primary energy (red square) and its breakdown per source compared to the baseline.

The total, electric and biomass GPIs are reported in Table 3. The DE scenario have the highest biomass GPI, but with a relatively high electric GPI. Overall, the total GPI is the lowest, meaning that the DE can decarbonized effectively the PPS.

Table 3. Total, electric and biomass GPI in MWh/t per scenario.

	CC	BIO	DE	IE
GPI_{total}	+2.0	+1.1	+0.6	+0.9
$GPI_{electric}$	+0.7	+1.4	+2.6	+2.8
$GPI_{biomass}$	+1.2	-0.3	-1.9	-1.9

To better understand what influences the GPIs, the total, electric and biomass GPI are breakdown by heat grade and subsector in Figure 4.

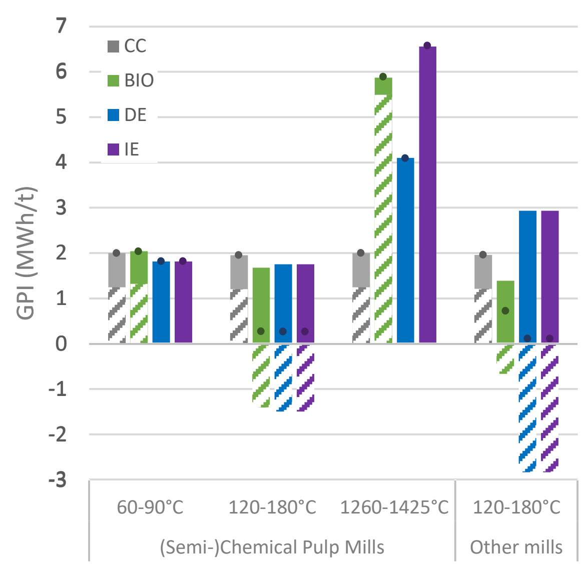

Figure 4. GHG performance indicator for electricity (solid bars), biomass (hatched bars) and total (dot).

The highest total GPI is for high-grade heat, reflecting that the usage is harder to abate than the others. The

CC scenario achieves the lowest total GPI, but CO_2 storage remains uncertain and the organic waste resource used to produce RNG is also limited - 25% of it is used in the CC scenario, based on the 2021 Quebec biomass inventory [24]. Therefore, the CC scenario's decarbonization solutions should be reserved for hard-to-abate industrial applications and residual emissions. The DE scenario ranks second, but it has the highest electric GPI across all heat grades and subsectors. The BIO scenario, relying mainly on wood residues, ranks third, with the lowest electric GPI and no need for additional biomass, as wood residues are redirected from steam production via HTHPs.

Sensitivity analysis

The sensitivity of three uncertain variables on the GPI is assessed in Table 4 using a one-at-a-time technique with lower and upper bound for each variable:

1. The proportion of heat provided by heat pumps, with bounds of 25% and 85%.
2. The reduction in energy demand from energy efficiency measures (EEMs), excluding heat pumps, with bounds of 10% and 20%. EEMs are apply to electricity for equipment (lighting, motors, compressors, etc.) and steam demand in (Semi-) mChemical Pulp Mills only.
3. The proportion of RNG in the gas blend, with bounds of 10% and 20%, including the change in natural gas fugitive emissions.

Table 4: Sensitivity analysis of variables on the GPI.

Scenarios	**$\Delta GPI_{electric}$ (%)**		**$\Delta GPI_{biomass}$ (%)**	
	LB	UB	LB	UB
1. Proportion of heat from HP and HTHP vs boilers				
	25%	85%	25%	85%
BIO	OB	+13%	OB	-185%
DE	+40%	-9%	-	-
IE	+36%	-9%	-	-
2. Reduction of electricity and steam consumption				
	10%	20%	10%	20%
CC	-18%	-19%	-18%	-51%
BIO	-16%	-19%	45%	324%
DE	-12%	-24%	-	-
ID	-11%	-22%	-	-
3. Proportion of RNG in the gas blend				
	10%	30%	10%	30%
CC	+7%	-7%	-50%	+50%

OB: Out of bounds

The sensitivity analysis results provide valuable insights: EEMs and waste heat recovery with heat pumps could significantly reduce additional electricity and limit unnecessary grid expansion. EEMs cutting steam and electricity demand of electric equipment by 10% and 20% could reduce additional electricity demand by 11%-18% and 18%-24%, respectively, depending on the scenario. EEMs should be implemented before or alongside electrification of process heat to reduce decarbonization's burden. They must also align with the chosen decarbonization pathway for effectiveness. Heat pump adoption is crucial in limiting electric demand. If heat pumps provide 25% of the process heat, additional electricity increases by 40% for the DE scenario, while providing 85% of the heat reduces additional electricity demand by 9%. These differences highlight the importance of characterizing the potential of heat pumps to minimize the capacities of electric boilers as much as possible.

The sensitive analysis shows that the proportion of RNG represents a trade-off between the organic waste demand and CO_2 storage requirements, both limited resources. At 30% RNG, organic waste demand rises to 37% of the available resource in Quebec for 2021. At 10% RNG level, CO_2 storage requirements to offset indirect emissions rises by 13% due to natural gas fugitive emissions.

CONCLUSION

This study provides a comprehensive analysis of the decarbonization pathways for the PPS and their impact on resource in Quebec. The results indicate that while all scenarios lead to 98-99% reductions in GHG emissions, the strategies employed have varying levels of efficiency. The CC scenario is notable for its low electricity demand and costs but requires uncertain CO_2 storage and large amounts of organic waste for RNG production. Carbon capture and RNG should be reserved for the hardest-to-abate applications among all industries. Further work is needed to determine whether the lime kiln falls into this category. The DE scenario, with a total GPI of 0.6 MWh/t, uses the least combined electricity and biomass to avoid one ton of CO_2. The sensitivity analysis highlights key variables like EEMs, heat pump integration, and the proportion of RNG in gas bend. EEMs and heat pumps are critical for minimizing grid expansion, and aligning EEMs with decarbonization pathways is vital for an effective energy transition. Future research should focus on cost-effectiveness assessments and expanding the model to optimize resource allocation across Quebec's major industries.

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