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Decarbonization Pathways for the Pulp and Paper Industry: An Emission-Centric Techno-Economic Assessment

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Decarbonization Pathways for the Pulp and Paper Industry: An Emission-Centric Techno-Economic Assessment

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ABSTRACT

The pulp and paper industry accounts for ~6% of global industrial energy use and ~2% of direct CO_2 emissions. This study develops a process-level energy and emissions model for an integrated Swedish kraft mill. Thermal and electrical demands were quantified using benchmark-specific energy consumption values, refined with first-principles models for drying, evaporation, and cooking. Emissions covered biogenic and fossil CO_2 from combustion and indirect electricity use. Drying (38%), evaporation (24%), and cooking (18%) dominated thermal demand, with recovery and bark boilers supplying most steam and contributing >50% of total CO_2 emissions. Three electrification pathways were assessed: electric boilers (EB), high-temperature heat pumps (HTHP), and mechanical vapour recompression (MVR). MVR reduced evaporator demand by ~92%, while complete substitution with low-carbon electricity cut mill emissions by up to 90%, depending on grid intensity. The framework integrates energy balances with techno-economic indicators, supporting process-level prioritization and cost-effective decarbonization.

Keywords: pulp and paper, decarbonization, electrification, emission abatement, energy efficiency, techno-economic assessment

Abbreviations	
EB	Electric Boiler
HTHP	High-Temperature Heat Pump
MVR	Mechanical Vapour Recompression
SEC	Specific Energy Consumption
LCOHt	Levelized Cost of Heat
NPV	Net Present Value
Symbols	
n	Year
Q	Energy
m	Mass flow
h	Enthalpy

1. INTRODUCTION

The pulp and paper industry comprises integrated mills, producing pulp and paper on-site, and non-integrated mills, relying on externally sourced pulp [1]. Pulp is obtained via mechanical, chemical, or combined methods, with Kraft pulping dominating and generating substantial biomass residues typically used for energy generation [2,3]. As a result, integrated mills are often energy self-sufficient and may be connected to local electricity and thermal grids to supply surplus energy, providing additional revenue streams. Non-integrated mills, on the other hand, often lack access to local biomass and are more dependent on fossil fuels for processes such as drying. This difference also influences the techno-economic evaluation of emissions, which may present distinct constraints compared to integrated mills. However, the focus of this paper is on a fully integrated plant.

Despite significant use of biomass for energy generation, the industry faces considerable environmental impact from production, transport, and disposal [4]. In response, a range of decarbonization strategies, such as biomass utilization, combined heat and power, recycling, and energy efficiency improvements, are being pursued. These efforts align with long-term sectoral goals, including an 80% reduction in CO_2 emissions by 2050, driven by both regulatory pressure and increasing global demand [4].

The objective of this work is to: (i) quantify energy use and CO_2 emissions at the process level for an integrated kraft pulp and paper mill, (ii) identify major thermal energy and emission hotspots, and (iii) evaluate the technical and economic potential of selected electrification technologies under varying electricity carbon intensities and policy scenarios.

2. METHODOLOGY

The methodology adopts a hybrid approach that begins with high-level average-value modelling from process data and progressively incorporates first-principle models or more detailed physical models, complementing the average-based model. The overall objective is to quantify energy consumption and associated emissions from fuel use across the pulp and paper value chain.

2.1 Process Flow Modelling

The initial stage constructs a process flow-based energy model, using literature-based average energy intensities and conversion factors. Two main inputs are required: the quantity of bleached pulp produced (air-dried tonnes, ADt) and the corresponding operating hours. Material flows are recursively estimated from final pulp output using process-specific conversion efficiencies [5]:

- Pulp screening and washing (97.8% efficiency).
- Oxygen delignification (96.1%).
- Bleaching (99.9%).
- Pulping from screened chips (50% yield).
- Chip preparation and debarking (99.3%).
- Raw wood to debarked chips (87.7%).

$$\boldsymbol{conversion\ efficiency} = \frac{\boldsymbol{process\ output}}{\boldsymbol{process\ input}} \quad (1)$$

Associated by-products are considered: biomass residues from debarking/screening (fuel for bark boiler), black liquor generation (8.5 tons per ton of unbleached pulp [6,7], concentrated from 15% to 85% solids) [8], and white liquor production (0.344 × black liquor). Paper production expands pulp output by 1.56, while tall oil pitch availability is based on 35 kg crude tall oil/t wood [9], with 25% recoverable [10]. This allows upstream material demand to be calculated recursively from the final output, incorporating efficiency or losses at each stage.

Specific energy consumption (SEC) as in **Table 1** is used to calculate the thermal and electrical energy consumption of an individual process.

$$\boldsymbol{SEC_{th/el}} = \frac{\boldsymbol{energy\ use_{th/el}}}{\boldsymbol{production}} \quad (2)$$

Energy supply is modelled for a typical Swedish integrated mill [5]. Biomass residues, black liquor, bark, and tall oil pitch are primary fuels in recovery boilers, bark boilers, and lime kilns.

The recovery boiler is prioritized for steam generation, supplemented by the bark boiler as needed. High-pressure steam drives a back-pressure turbine, generating electricity and extracting medium- and low-pressure steam for process use. Key balances include:

- Heat from black liquor and recovery boiler output.
- Supplementary steam from bark boiler
- Process steam balance
- Turbine electricity generation (and grid electricity import, if required.

Table 1: Benchmark specific energy consumption [5]

Process	Electric (kWh per ADt of Pulp)	Thermal (GJ per ADt of Pulp)
Debarking	10	-
Chipping and conveying	35	-
Digester	44	1.55
Washing	60	-
Oxygen Delignification	60	0.08
Bleaching	80	0.22
Evaporators	27	3.49
Recovery Boilers	80	-
Causticizer & Lime Kiln	59	-
Pulp Refiners	75	-
Forming	227	-
Pressing	156.75	-
Drying	57	4.23
Finishing	33.25	-

Table 2: Fuel Properties [9,11,12,13]

Black Liquor		
Emission Factor	91.00	Kg CO_2/GJ
Heating Value	14.00	kJ/kg
Bark Biomass		
Emission Factor	97.22	Kg CO_2/GJ
Heating Value	13.20	kJ/kg
Tall Oil Pitch		
Emission Factor	76.60	Kg CO_2/GJ
Heating Value	38.00	kJ/kg

Emissions are quantified using fuel-specific factors for each combustion unit (**Table *2***). The model distinguishes:

- **Biogenic emissions** from black liquor, bark, and tall oil pitch.
- **Non-biogenic emissions** from fossil inputs.
  Indirect emissions from imported electricity are included via grid-specific factors.

High-energy or high-emission processes identified in the average value-based model are replaced with first-principle-based sub-models. These detailed models, grounded in thermodynamic and process engineering principles, enhance the precision and adaptability of the overall framework.

2.2 First Principles Models

This approach provides a physics-based representation of energy transformation, enhancing accuracy in estimating energy demand under varying operational conditions. The first-principles models replace the average-value representations of energy-intensive units, enabling mill-specific simulations based on mass and energy conservation, thermodynamics, and heat transfer. Three processes were selected for detailed modelling due to their high energy intensity: the paper machine dryer section, black liquor evaporator, and pulp digester.

Paper Machine (Dryer Section)*:* The dryer evaporates water using thermal energy, with heat transfer by conduction from steam-heated cylinders and convection from hot air. The model applies steady-state mass and energy balances, linking inlet–outlet moisture content to steam demand through the latent heat of vaporization.

Assumptions: solids content increases from 50% to 92% **[14,15]**, dryer efficiency 80% (η_{dryer}), dryer share of paper machine energy 60% (C_{dryer}) [16].

$$\boldsymbol{m_{eva}} = \frac{\boldsymbol{P * X_{paper}}}{\boldsymbol{X_{entry}}} - \frac{\boldsymbol{P * X_{paper}}}{\boldsymbol{X_{exit}}} \ [\boldsymbol{GJ/day}] \quad (3)$$

$$\boldsymbol{Q_{eva}} = \frac{\boldsymbol{m_{eva} * h_{vap}}}{\boldsymbol{\eta_{dryer} * C_{dryer}}} \ [\boldsymbol{GJ/day}] \quad (4)$$

Calculations include water mass evaporated (m_{eva}), total steam demandQ_{eva}, where X_{paper}, X_{entry} and X_{exit} are the solid mass fractions on the final paper web, the web at the entry of the dryer and the web at the exit of the dryer, respectively. P is the mass flow rate of Paper Produced and h_{vap} is the enthalpy of vaporisation.

Black Liquor Evaporator: Weak black liquor (15% solids at entry) is concentrated to strong liquor (80% solids at exit) using a seven-effect evaporator system **[8]**. A mass balance determines water removal m_{eva}, and live steam demand is calculated using steam economy (6.2 kg water/kg steam). Assumptions: inlet pressure 3.5 bar, temperature 150°C, h_{steam} enthalpy 2748 kJ/kg [5].

$$\boldsymbol{Q_{eva}} = \frac{\boldsymbol{m_{eva} * h_{steam}}}{\boldsymbol{steam\ economy}} \quad (5)$$

Steam economy is defined as the amount of water evaporated per the amount of steam required at the first effect of the evaporator.

Pulp Digester: The digester chemically converts wood chips to pulp through thermal and chemical zones. The model incorporates energy required for heating, delignification (exothermic), and washing.

Heating zone: The energy required to increase the temperature of wood chips and cooking liquor from 120°C to 170°C [3].

$$\boldsymbol{Q_{wc}} = \frac{\boldsymbol{m_{wc} * Cp_{wc} * (T_{out} - T_{in})}}{\boldsymbol{\eta_{hx}}} \quad (6)$$

$$\boldsymbol{Q_{cl}} = \frac{\boldsymbol{m_{cl} * Cp_{cl} * (T_{out} - T_{in})}}{\boldsymbol{\eta_{hx}}} \quad (\mathbf{7})$$

$$\boldsymbol{Q_1} \left[\frac{\boldsymbol{MJ}}{\boldsymbol{day}}\right] = \boldsymbol{Q_{wc}} + \boldsymbol{Q_{cl}} \quad (8)$$

Exothermic energy released during delignification:

$$Q_2 = m_{lignin,extracted} * 619 \ [MJ/day]$$

Washing zone: Energy required to increase the temperature from 80°C to 120°C.

$$\boldsymbol{Q_3} \ [\boldsymbol{MJ/day}] = \frac{\boldsymbol{m_{wl} * Cp_{wl} * (T_{out} - T_{in})}}{\boldsymbol{\eta_{hx}}} \quad (9)$$

Parameter inputs: liquor-to-wood ratio 4:1 **[17]**, pulp yield, lignin content (27%) **[18]**, heat capacities of wood and liquor, heat exchanger efficiency (90%).

$$\textbf{Total Energy: } \boldsymbol{Q} = \boldsymbol{Q_1} + \boldsymbol{Q_2} + \boldsymbol{Q_3} \ [\tfrac{\boldsymbol{MJ}}{\boldsymbol{day}}] \quad (10)$$

External Processes

In order to broaden the value chain, Forestry, pre-transportation, and post-production logistics are included at a system level to capture life-cycle emissions, particularly from fossil fuel-based transport.

2.3 Electrification Technologies

The assessment employs a comparative framework to evaluate the potential of alternative technologies to reduce energy consumption and emissions in high-impact processes within a pulp and paper mill.

Electrification technologies are proposed as replacements for conventional high-impacting systems while maintaining production output. The energy use of each alternative is estimated from literature, technical data, or benchmarks. This enables a direct comparison with conventional systems:

- **EBs** (cross-sectoral): direct conversion of electricity to steam, efficiency 95% [19].
- **HTHPs** (cross-sectoral): recovery of low-temperature waste heat, delivering heat at 160°C, COP 3.6 [20].
- **MVR** (sector-specific): compression of low-pressure vapour for reuse in black liquor evaporation, COP 10 [21].

The energy savings and emission reductions will be calculated from the reference case to the one with electrified equipment.

2.4 Sensitivity Analysis

The sensitivity analysis explores how electricity carbon intensity shapes the environmental feasibility of mill electrification. It establishes a breakeven threshold—the weighted average carbon intensity of conventional steam generation—below which electrification is favourable.

Derived from the conventional fuel mix, this threshold provides the benchmark for evaluating the comparative benefits of electrification technologies.:

$$\boldsymbol{EF_{breakeven}} = \sum (\boldsymbol{x_i} * \boldsymbol{EF_i}) \qquad (11)$$

Where x_i is the energy share of fuel in steam production, and EF_i is the emission factor. For the benchmark Swedish mill, dominated by black liquor and bark, the breakeven value is 0.3315 kg CO_2/kWh. The analysis compares Sweden (baseline, 0.041 kg CO_2/kWh [22]) with three additional scenarios representing countries with increasing fossil shares in their electricity mix: Scenario A (0.072 kg CO_2/kWh), Scenario B (0.384 kg CO_2/kWh), and Scenario C (0.708 kg CO_2/kWh) **[23].**

2.5 Economic Evaluation

Table 3: Economic input assumptions ***[24]***

Parameter	Unit	EB	HTHP	MVR
Capex	€/kW	150-200	200-2000	250-500
Fixed O&M	€/kW	1% of Capex	2% of Capex	3# of Capex
Variable O&M	€/kWh	0.0026	0.0017	0
Discount Rate		10	10	7
Lifetime		20	20	20
Electricity Price	€/kWh	.03 - .09	.03 - .09	.03 - .09

The economic feasibility of proposed decarbonization technologies is evaluated using certain indicators: levelized cost of heat (LCOHt), net present value (NPV), insights into cost competitiveness, profitability, and payback period. The analysis incorporates realistic input assumptions, as in **Table *3*.**

3. RESULTS

3.1 Process flow model results

The process-flow model shows that drying, evaporation, and digestion account for 97.4% of the total thermal energy demand (23 404 GJ/day), with the paper dryer using 56.4% of steam input, black liquor evaporator 27.7%, and continuous digester 13.3%. Steam is mainly generated by recovery and bark boilers, yielding 38 431 GJ/day and an exportable 11 881 GJ/day surplus and associated CO_2 emissions total 5 244 t/day, with black liquor combustion responsible for 80.5%. Electricity generation from the back-pressure turbine reaches 2.30 GWh/day, nearly meeting the demand of 2.58 GWh/day; 0.28 GWh/day is imported, and surplus electricity is occasionally exported.

3.2 First-Principle Model Results

The sub-models confirmed the high intensity of the three largest units. Total energy demand is dominated by drying (36.8%), followed by evaporation (20.2%) and digestion (12.0%), as in **Figure 1**. External processes add ~8% to the footprint, with transport, forestry, and pre-transport as key contributors. Emission analysis shows these external activities are the main source of non-biogenic emissions driven by fossil fuel-based logistics, as in **Figure 2.**

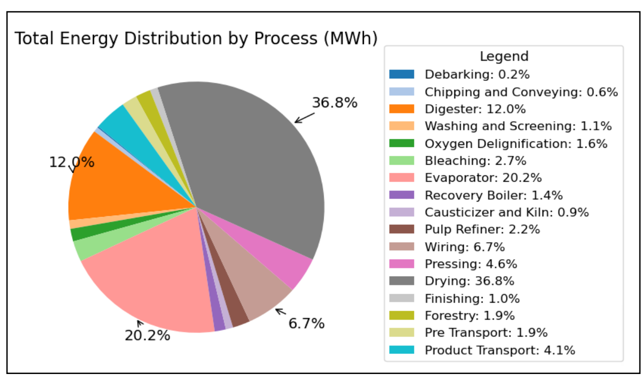

Figure 1: Total energy consumption distribution

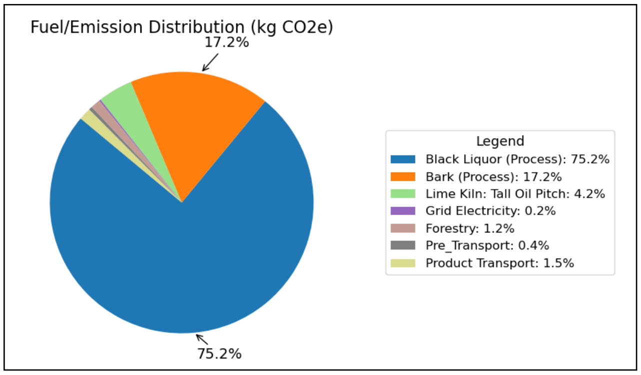

Figure 2: Fuel emission distribution

3.3 Alternate Technology Assessment

Integration of electrification technologies showed strong abatement potential as illustrated in **Figure 3**

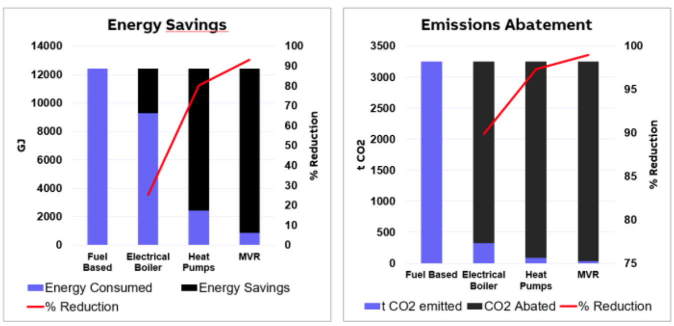

Figure 3: Alternate technologies analysis

- MVR: Retrofitting reduced evaporator steam demand by 93%, lowering boiler load and emissions by ~99%.
- HTHP: Drying-loop integration cut steam demand by 50–60%; with COP 3.6, overall thermal use decreased ~80% versus baseline.
- EB: Enabled full steam electrification but without efficiency gains, shifting all demand to electricity.

3.4 Sensitivity Analysis

The sensitivity analysis demonstrated that the environmental viability of electrification is highly dependent on the carbon intensity of electricity. A threshold value of approximately **0.33 kg CO_2/kWh** was identified, below which electrification yields lower emissions than biomass-based steam generation.

3.5 Economic Feasibility

Economic assessment of electrification technologies—EB, HTHP, and MVR—showed negative NPVs and no viable payback without incentives, due to cost-neutral biomass-based steam and largely biogenic emissions. LCOHt ranged 0.003–0.010 €/kWh (MVR), 0.010–0.034 €/kWh (HTHP), and 0.037–0.101 €/kWh (EB). Lignin valorization at €100/t slightly improved economics but remained unprofitable. A €134/t CO_2 carbon tax rendered all options viable, with paybacks of 0.04–1.85 years depending on process and technology. Electrification is thus technically promising, though financial feasibility depends on policy support and byproduct valorization.

4. DISCUSSION

The results highlight that drying, evaporation, and digestion are the dominant thermal energy consumers in the pulp and paper industry. Their high shares reflect fundamental process requirements: the evaporation of large water fractions during paper drying, the concentration of black liquor in multi-effect evaporators, and the sustained high-temperature cooking of wood chips in the digester. These intrinsic thermodynamic demands account for nearly all steam consumption, even in modern mills with efficiency measures implemented.

On the electrical side, wiring, pressing, and pulp refining emerged as the largest consumers. These operations involve high mechanical loads for fiber processing, water removal, and sheet consolidation, resulting in substantial electricity demand. However, electricity constitutes a smaller share compared to total thermal demand, emphasizing that thermal processes dominate mill energy balances and that decarbonization efforts must primarily focus on steam generation and use.

Non-biogenic emissions originate mainly from external energy inputs and fossil-based auxiliary fuels, such as fossil-based fuels in the lime kiln, as well as imported electricity under carbon-intensive grid conditions. This indicates that emission abatement strategies cannot rely solely on internal biomass cycles and must account for electricity system characteristics.

Electrification potential is region- and mill-specific. MVR is universally favourable, while EBs and HTHPs require supportive conditions, including low-carbon electricity, competitive tariffs, or access to co-product valorization, such as lignin. Economic feasibility is limited without intervention; policy instruments, process-integrated savings, and by-product valorization can improve competitiveness and payback periods.

5. CONCLUSIONS

This study highlights the high thermal energy demand in the pulp and paper industry, mainly supplied by biogenic and fossil-based steam. Electrification technologies, sector-specific and cross-sectoral, can reduce emissions, though effectiveness depends on low-carbon electricity. Sector-specific solutions deliver strong impact but limited applicability, while cross-sectoral options are broadly relevant with moderate gains; hybrid strategies may balance trade-offs. Decarbonization requires grid low-carbonization or local renewable integration, supported by policies and incentives. Limitations include reliance on first-principle and averaged models and partial value-chain coverage.

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