

INDUSTRIAL DECARBONIZATION SERIES · MAY 2026

PULP & PAPER DECARBONIZATION

Process emissions, carbon markets, and capital discipline on the path to net zero.

A CLIMATE DECODE WHITE PAPER

Part of the Climate Decode industrial decarbonization series

CLIMATE DECODE

Executive Highlights

Pulp & paper sits at the intersection of three forces shaping industrial decarbonization: capital scarcity, tightening carbon regulation, and a fast-evolving market for carbon credits and tax incentives. The mills that win the next decade will be those that convert this complexity into a coherent investment plan.

~401 MtGLOBAL PAPER &
PAPERBOARD OUTPUT,**~2%**SHARE OF INDUSTRIAL CO₂
EMISSIONS**~6%**SHARE OF INDUSTRIAL
ENERGY USE**~85%**FOSSIL SCOPE-1 IN BOILER +
LIME KILN

Purpose of this paper

- Set out the decarbonization toolkit available to pulp & paper (P&P) mill operators in operational, not aspirational, terms.
- Connect mill-level data to an emissions baseline, then to a marginal abatement cost (MAC) curve, then to a financing plan that captures every available revenue layer.
- Show, through two worked case studies, how compliance carbon prices, tax credits, fuel-side credits, and voluntary removal credits combine to determine which projects actually clear an investment committee.

State of the industry

- Global paper and paperboard output reached approximately 401 million tonnes (Mt) in 2024; wood-pulp output approximately 189 Mt.
- Packaging and tissue dominate growth; graphic paper continues its long decline.
- China is the largest paper producer (~125 Mt); the U.S. and China are roughly tied as the largest wood-pulp producers; Brazil, Canada, and Sweden round out the top five.
- The sector consumes roughly 6% of global industrial energy yet contributes only about 2% of industrial CO₂ — a gap driven by reliance on biogenic fuels (black liquor, bark, biomass) rather than fossil sources.

Where the emissions sit

- Fossil Scope-1 emissions are concentrated: the natural-gas (NG) package boiler and the lime kiln together account for roughly 85% of fossil Scope-1 emissions at a typical kraft mill.
- Biogenic CO₂ from black-liquor and biomass combustion runs at approximately 280 ktCO₂/yr at the hypothetical 200 kADt/yr mill used in this paper — the sector's most under-utilized opportunity for engineered negative emissions.
- Scope-2 exposure varies sharply with grid carbon intensity, from near-zero in hydropower jurisdictions to 50–60 ktCO₂/yr in fossil-heavy grids for the same load.
- Paper-machine drying is the single largest steam duty, followed by the kraft digester, ECF bleaching, and black-liquor evaporators.

The decarbonization toolkit

- Energy efficiency — closed dryer hoods, shoe presses, heat recovery and integration, mechanical vapour recompression (MVR) — is the always-on first wave; mostly negative-MAC.

- Fuel switching — renewable natural gas (RNG), on-site biogas, low-carbon hydrogen, biomass gasification, pulverized biomass, LignoBoost — targets the lime kiln and the NG package boiler.
- Electrification — industrial heat pumps and electric boilers — replaces fossil heat with electricity; the case depends on the local electricity-to-NG price ratio and grid carbon intensity.
- Process innovation — black-liquor gasification (BLG), borate auto-causticizing — is gated by the natural replacement cycle of the equipment being displaced.
- Bioenergy with carbon capture and storage (BECCS) produces verified negative emissions but is excluded from compliance markets; economics depend on tax credits and voluntary removal offtake.
- Recycled-fibre (RCF) substitution and broader circularity reduce upstream pulping energy and act as a sequencing variable for the rest of the portfolio.

Challenges to deployment

- Upfront capital is the binding constraint — modern integrated mills carry USD \$1–2 billion greenfield CAPEX and 30–50-year asset lives, so decarbonization economics tighten outside the natural replacement window.
- Fuel-switching cost gap — green hydrogen at USD \$4–6/kg today implies abatement well above \$200/tCO₂ before policy support.
- Policy support varies by jurisdiction and steps down on a fixed schedule; mills in regions without comparable instruments face very different project economics.
- Technology readiness level (TRL) sits at 6–8 for several of the highest-impact levers, carrying first-of-a-kind integration risk.
- Carbon-market and voluntary-market prices remain volatile; the durable-removal VCM is anchored by a narrow set of corporate buyers, and long-dated offtake contracts are the gating step for any BECCS project.
- Workforce capacity — engineers, operators, and maintenance technicians qualified for industrial heat pumps, amine capture, and hydrogen burners — is a real constraint with a five-to-ten-year training lead time.

The take-aways

Sequencing matters: energy efficiency first, then RCF where fibre quality permits, then electrification on the residual load, then BECCS or BLG once the steam-electricity-CO₂ ledger is balanced. Reversing this sequence regularly leaves 15–30% of cost-effective abatement on the table. Policy certainty — not technology, and not the headline carbon-price level — is the binding constraint at the project level. Mills that build an analytical workflow connecting operations data to emissions to a MAC to financing structurally outperform mills that commission one-off studies.

SECTION 01

State of the Industry

01

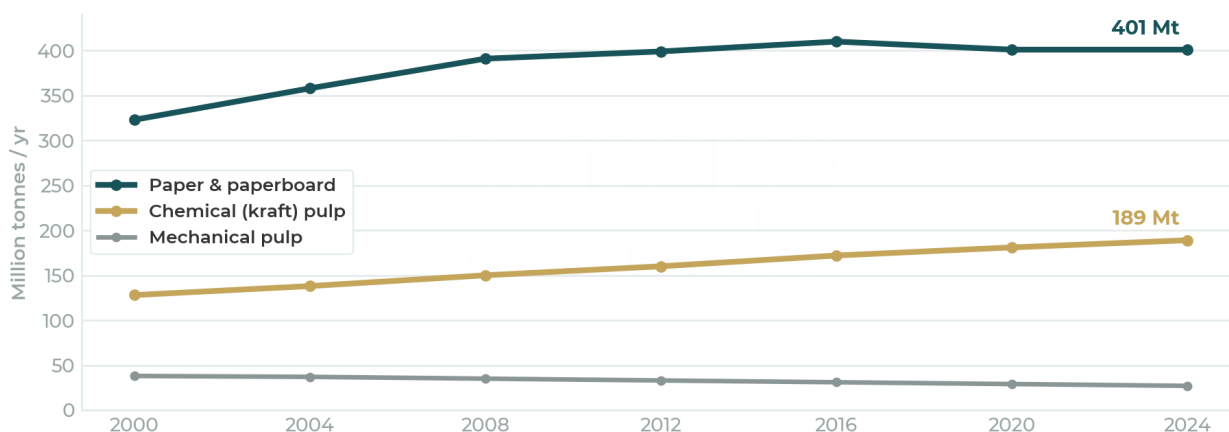
Pulp & paper is one of the world's largest energy-intensive manufacturing sectors and one of the most globally distributed. It supplies the fibre behind almost every form of packaging, printing, hygiene, and speciality paper product, and its facilities sit close to either the forests that supply their fibre or the population centres that consume the end product. Although the sector is large in absolute energy terms, its climate footprint is structurally distinctive — it draws most of its thermal energy from biogenic fuels recovered within the mill itself, so it accounts for a much smaller share of global industrial emissions than its energy intensity alone would suggest. This first section maps the production volumes, geographic distribution, and emissions profile that frame the decarbonization discussion in the rest of the paper; the production processes themselves and the energy intensity of each step are covered in Section 2.

1.1 Production Growth and Geography

Global wood-pulp output rose 3% to 189 million tonnes (Mt) in 2024, while paper and paperboard production reached approximately 401 Mt. China is the world's largest paper and paperboard producer and consumer, accounting for roughly 125 Mt of annual output and an even larger share when recycled fibre is counted in the fibre furnish; the United States is the second-largest paper producer at around 70 Mt. For wood-pulp production specifically, the United States (35.9 Mt) and China (31.7 Mt) are roughly tied at the top, with China closing the gap rapidly; Brazil (the world's largest market-pulp exporter), Canada, and Sweden round out the top five wood-pulp producers. Demand has structurally shifted over the past decade: graphic paper (newsprint and writing) is in long-term decline; packaging — pulled by e-commerce, food service, and plastic-substitution mandates — and tissue dominate new growth.

Figure 1 • Global pulp & paper production, 2000 to 2024

Total paper has plateaued near 400 Mt while chemical pulp grows at the expense of mechanical pulp.



Source: FAO Forest Products Statistics 2024; CEPI Key Statistics. Series indicative of stated 2024 endpoints.

Figure 1. Global pulp and paper production 2000–2024. Total paper has plateaued near 400 Mt while chemical pulp continues to grow at the expense of mechanical pulp.

1.2 Emissions Footprint Relative to Other Industries

The P&P sector is assigned roughly 2% of global industrial CO₂ emissions despite consuming about 6% of industrial energy. The gap reflects the sector's biogenic fuel base — black liquor, bark, and biomass make up over two-thirds of typical mill steam and produce CO₂ that is not counted as fossil under the GHG Protocol, ISO 14064, or the Western Climate Initiative (WCI) and U.S. Greenhouse Gas Reporting

Program (GHGRP) frameworks. Applying standard combustion emission factors to the sector's published energy mix puts fossil emissions in the range of approximately 150–200 Mt CO₂/yr and biogenic CO₂ from black-liquor and biomass combustion on the order of 500–600 Mt CO₂/yr. The biogenic portion is the sector's most under-utilized opportunity for negative emissions, but it requires both technology and policy access to be unlocked.

Figure 2 • Pulp & paper — 2% of industrial CO₂, 6% of industrial energy

The gap is driven by the sector's biogenic fuel base (black liquor, bark, biomass).

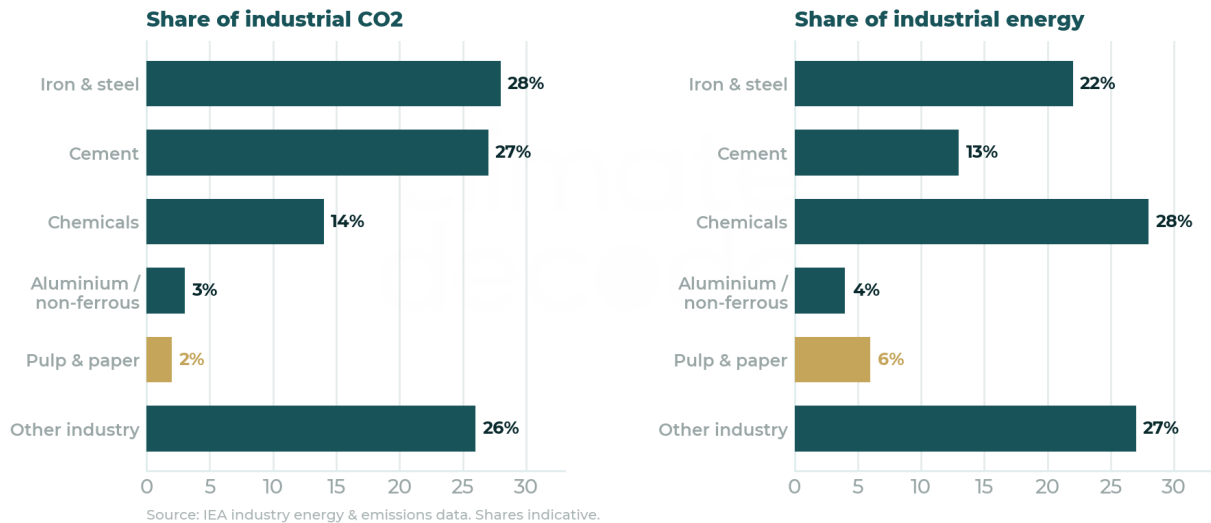


Figure 2. Industrial CO₂ emissions (left) and final energy consumption (right) by sector. Pulp & paper accounts for only 2% of industrial CO₂ but 6% of industrial energy — the gap is driven by the sector's biogenic fuel base.

SECTION 02

The Production Process and Its Energy Profile

02

Modern P&P mills convert wood (or recycled fibre) into market pulp, paper, or paperboard through three stages: raw material preparation, pulping, and papermaking. Pulp can be produced by three routes — chemical (kraft or sulfite), mechanical (thermo-mechanical pulping (TMP), refiner-mechanical, groundwood), and recycled fibre (RCF). Most modern North American and Nordic facilities are integrated kraft + paper mills with optional RCF blending. The figure below summarizes the integrated kraft + paper material and energy flow.

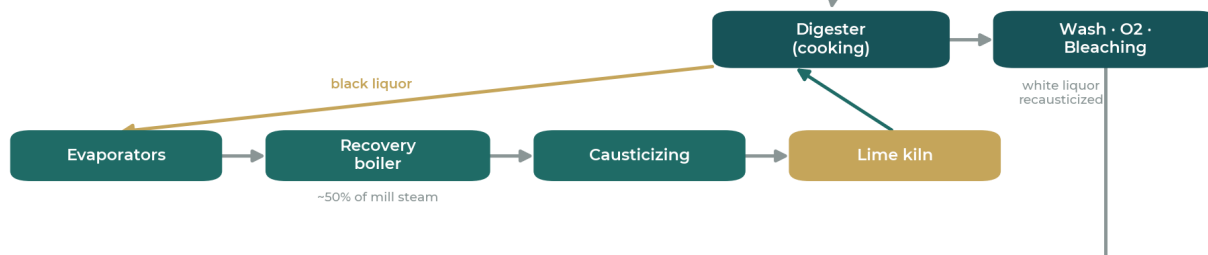
Figure 3 • Integrated kraft + paper mill — material & energy flow

The kraft chemical-recovery loop (digester to evaporators to recovery boiler to causticizing to lime kiln) makes the mill near energy self-sufficient.

RAW MATERIAL PREPARATION



PULP PRODUCTION (KRAFT)



PAPER MAKING



Figure 3. Integrated pulp & paper production — process flow across raw-material preparation, kraft pulping with its chemical-recovery loop, and paper making. The kraft recovery cycle (digester to evaporators to recovery boiler to causticizer to lime kiln to digester) makes the kraft process energy-self-sufficient.

2.1 Raw Material Preparation

Wood arrives at the mill as logs from forests, plantations, or sawmill residues. Before pulping, it must be cleaned, sized, and quality-graded through three steps — debarking, chipping, and screening — that together account for roughly 10% of mill electricity but only a small fraction of mill thermal demand.

The first step is debarking. Logs are tumbled in a rotating drum where contact between the logs strips off the outer bark. Longer drum residence delivers a cleaner debark but loses more usable wood and uses more electricity, with typical energy consumption around 8.5 kWh per tonne of wood. The bark removed at this stage is routed directly to the biomass boiler, where it provides roughly 80–120 kg of biogenic fuel per tonne of pulp produced and contributes to the mill's on-site energy supply.

Debarked logs then move to the chipper, where they are cut into 2–4 cm chips using disc or drum chippers. Chip size is critical to the rest of the mill: chips that are too thick prevent cooking chemicals from reaching the centre, while chips that are too small or fragmented disrupt flow through the digester. Chipping and conveying together consume approximately 30 kWh per tonne of wood. Chips are then screened by size, with oversized pieces and fines diverted away from the mainstream; a narrow

size distribution improves cooking uniformity downstream and reduces chemical consumption.

2.2 Pulp Production — Three Routes

Wood is roughly half cellulose fibre and half a lignin polymer that binds the fibres together. Pulping is the act of separating the two. There are three ways to do it: chemically (dissolve the lignin), mechanically (force the fibres apart), or by re-pulping recovered paper. Each route has a different yield and energy profile, and produces pulp suited to different paper grades.

TABLE 1

Comparison of the three pulping routes — chemical (kraft), mechanical (TMP/RMP/GW), and recycled fibre (RCF).

Attribute	Chemical (Kraft)	Mechanical (TMP/RMP/GW)	Recycled Fibre (RCF)
Share of virgin pulp	~70%	~20%	n/a (uses RCF feedstock)
Yield (pulp / wood)	45–55%	90–95%	65–85% (after rejects)
Lignin handling	Dissolved chemically	Retained in fibre	Pre-existing in fibre
Dominant energy vector	Steam (digester + recovery + drying)	Electricity (refining)	Electricity (slushing, refining)
Total energy (GJ/ADt)	13–16	10–14 (mostly electricity)	5–9
Typical end-use grades	Linerboard, market pulp, fine paper, tissue	Newsprint, magazine, mech-board	Linerboard, tissue, container

2.2.1 Chemical (Kraft) Pulping

Kraft is the dominant pulping route worldwide, producing about 80% of global chemical pulp. Wood chips are cooked in a large, pressurized vessel called a digester with a hot alkaline mixture (sodium hydroxide and sodium sulfide, known as white liquor) at around 165 °C and 7 bar. The chemistry dissolves the lignin and releases the cellulose fibres. About half of the wood mass leaves as usable pulp; the rest leaves as a dark spent liquor (black liquor) that is the foundation of the mill's energy supply.

Inside the digester, the chips pass through a sequence of zones — pre-steaming to drive out air, impregnation in cooking liquor at moderate temperature, heating to full cooking temperature, the cooking reaction itself, then liquor extraction and washing. The digester alone uses about 4.5 GJ of steam and 400 kWh of electricity per tonne of pulp. After cooking, the pulp is washed, treated with oxygen to remove residual lignin, screened, and bleached. Bleaching uses chlorine dioxide to lift brightness to market specification and is the most chemical-intensive step, consuming a few GJ of steam and 60–185 kWh per tonne. If the pulp is shipped to a separate paper mill, it is then dried at the cost of another ~4.5 GJ/tonne; integrated mills skip drying and feed the pulp wet to the paper machine.

The defining feature of kraft is the chemical recovery cycle. The black liquor extracted from the digester is concentrated in evaporators and burned in a recovery boiler. Combustion serves three purposes at once: it generates high-pressure steam that drives turbines and process heat, it recovers the inorganic chemicals as a molten smelt at the boiler floor, and it disposes of the lignin so it does not become a waste stream. The recovered chemicals are dissolved in water (green liquor), reacted with lime (causticizing) to regenerate fresh cooking liquor, and the spent calcium carbonate is fired back to lime in the lime kiln. The lime kiln burns natural gas (occasionally heavy fuel oil at older sites) and consumes about 1.2 GJ/tonne of direct fuel — the dominant fossil-fuel load in an otherwise biogenic-fuel mill. Closed-loop chemical recovery captures 98% of the cooking chemicals; this is what makes a kraft mill close to energy self-sufficient.

2.2.2 Mechanical Pulping

Mechanical pulping separates fibres by force rather than chemistry. Wood is pressed against rotating grindstones or fed between high-speed metal refiner discs; friction and shear break the fibres apart while leaving the lignin in place. Because nothing is dissolved away, yield is high — 85–95% of the wood mass leaves as pulp — but the fibres are shorter and weaker, and the pulp tends to yellow with age. Mechanical pulp is typically used for newsprint, magazines, and lower-end packaging, often blended with stronger kraft fibre where strength matters.

Three sub-types dominate. Groundwood (GW) pulping presses logs against a rotating grindstone and is the lowest-electricity option at 1,100–2,200 kWh per tonne, with no steam input. Refiner-mechanical pulping (RMP) feeds chips between metal refiner discs at 1,600–3,000 kWh per tonne and also operates without steam. Thermo-mechanical pulping (TMP) pre-heats the chips with steam (approximately 0.03–0.93 GJ per tonne) before refining, producing stronger fibres at slightly higher electricity demand of 1,800–3,600 kWh per tonne. Across all three sub-types, washing and screening adds another 50 kWh per tonne, and bleaching with peroxide or hydrosulfite adds approximately 100 kWh per tonne for grades requiring optical brightness. Crucially, mechanical pulping has no black-liquor recovery cycle: the mill has no on-site biogenic boiler fuel beyond bark and must source steam from natural gas, purchased biomass, or electric boilers — making mechanical-pulp mills noticeably more grid-electricity-dependent and more exposed to grid emission factors in coal-heavy jurisdictions.

2.2.3 Recycled-Fibre (RCF) Pulping

Recycled-fibre pulping starts with recovered paper instead of fresh wood. Because the original mill has already done the chemical separation, the digester, evaporators, recovery boiler, causticizer, and lime kiln are all skipped — eliminating the most energy-intensive steps in the kraft process.

The flow is short. Slushing disperses the recovered paper in hot water using mechanical agitation, breaking the fibre network without damaging individual fibres (~390 kWh/tonne). Screening and cleaning remove staples, plastics, sand, and other contaminants (~50 kWh/tonne). For grades that require high brightness — graphic and fine office paper — a de-inking stage uses surfactants and flotation cells to lift ink particles out of the suspension (~80 kWh/tonne). Concentration and dispersion remove water before the pulp enters the paper machine (~0.54 GJ + 40 kWh per tonne); optional bleaching adds another ~30 kWh.

Total RCF energy intensity is 5–9 GJ per tonne — roughly half of integrated kraft. RCF is the largest single source of paper fibre globally; more than half of all paper made today uses recycled fibre, predominantly in linerboard, container grades, and tissue. The structural constraint is fibre quality: each cycle of recycling shortens the cellulose fibres and weakens the resulting pulp. Beyond five to seven cycles, the pulp is too weak for most product specifications without an injection of virgin kraft fibre. So RCF is bounded both by collection logistics on the supply side and by the strength requirements of the end product.

2.3 Paper Making

Once pulp has been produced, by any route, it is converted to paper, paperboard, or tissue on a paper machine — the largest single piece of equipment in the mill and the largest single consumer of both electricity and steam. It is also where most of the paper's final properties — basis weight, strength, smoothness, opacity — are set. The same four functional steps occur on every paper machine, regardless of grade: forming, pressing, drying, and finishing.

The first stage is stock preparation. The pulp slurry is conditioned to the requirements of the target grade through refining — mechanical treatment in disc refiners that adjusts fibre length and surface chemistry so the fibres bond well into a strong, smooth sheet. Different pulps are blended at this stage (kraft for strength, mechanical or recycled fibre for bulk and opacity), and mineral fillers and chemical additives are introduced. Refining alone draws several hundred kilowatt-hours per tonne of paper.

From stock preparation the slurry passes to the forming section. The headbox distributes a dilute pulp suspension (about 1% fibre) evenly across the width of the moving forming fabric, where water drains by gravity and vacuum, leaving a sheet at roughly 20% fibre content. Vacuum systems and fabric drives in the forming and press sections together account for around 30% of total paper-machine electricity. The press section follows, squeezing the formed sheet between felts and rollers to lift fibre content from about 20% to 45–50%. Every percentage point of dryness gained at the press saves about 4% of downstream drying steam.

Drying is the most energy-intensive step in paper-making and one of the largest steam duties in the whole mill. The paper web passes over a series of steam-heated cylinders that evaporate the remaining water, while hot air circulating through the dryer hood removes the vapour. Drying proceeds in three phases — a brief warm-up, a constant-rate phase where surface water evaporates, and a falling-rate phase where moisture must diffuse from inside the sheet to the surface before it can leave. The falling-rate phase is the slowest and the biggest energy consumer. Energy use varies sharply across grades, as the table below shows.

TABLE 2

Representative paper-machine energy intensity by grade.

Paper grade	Forming + pressing (kWh/t paper)	Drying steam (GJ/t paper)
Newsprint	422	4.29
Printing (coated)	528	5.48
Writing (uncoated)	528	5.27
Tissue	533	4.22
Packing paper / linerboard	270	4.22

2.4 Energy Intensity by Process and Product

Two structural patterns shape mill-level energy use. First, on the pulping side, the routes have very different energy profiles: mechanical pulping is electricity-heavy (~2,200 kWh per tonne, with little steam); chemical kraft is steam-heavy (~16 GJ of gross process steam, of which roughly more than half is supplied internally by black-liquor combustion, leaving 5–7 GJ of net external demand); recycled fibre is by far the lowest at about 2.7 GJ total. Second, on the paper-making side, drying steam dominates every grade at 4.2–5.5 GJ per tonne of paper, making the dryer the single highest-leverage decarbonization target whatever the product mix.

Figure 4 • Energy intensity by pulping route and paper grade

Mechanical pulping is electricity-dominated; kraft is steam-dominated; drying steam dominates every paper grade.

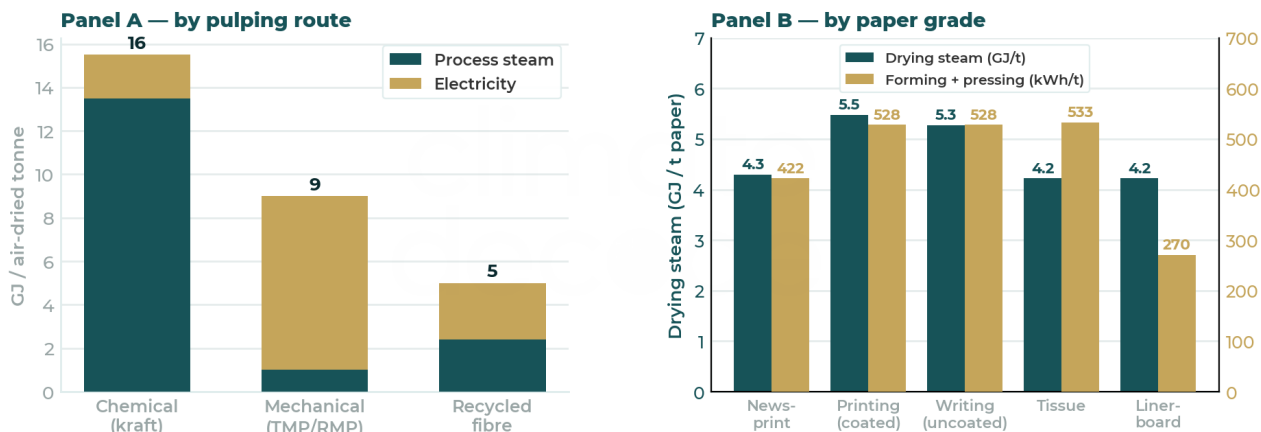


Figure 4. Energy intensity by pulping route (Panel A) and paper grade (Panel B). Mechanical pulping is electricity-dominated (~2,200 kWh/tAD); chemical kraft is steam-dominated; RCF is the lowest. Drying steam dominates (~4.2–5.5 GJ/t paper) across all grades.

2.5 Mill-Level Energy Use, Fuel Mix, and Per-Process Profile

A typical integrated kraft mill consumes 14–16 gigajoules (GJ) of total final energy per air-dried tonne (ADt) of pulp, of which roughly 10–12 GJ/ADt is delivered as process steam and 600–800 kilowatt-hours per ADt (about 2.2–2.9 GJ/ADt) is electricity — a split of approximately 75% thermal to 25% electrical. Steam therefore dominates total energy use. Four process steps stand out for steam consumption, each drawing between 4 and 5 GJ per tonne of product — paper-machine drying (~5.3 GJ/t), black-liquor evaporation (~4.4 GJ/t), the kraft digester (~4.4 GJ/t), and ECF bleaching (~4.3 GJ/t). Together they represent approximately four-fifths of total process-steam demand. On the electricity side, paper-machine forming and pressing combined draw around 530 kWh per tonne of paper, mechanical refining adds several hundred kWh per tonne where the mill includes a mechanical-pulp line, and bleach-plant pumping and oxygen-delignification compressors add roughly 100–150 kWh per tonne.

Figure 5 • Per-process energy intensity — integrated kraft + paper mill

Steam is dominated by drying and black-liquor evaporation; electricity by paper-machine forming and pressing.

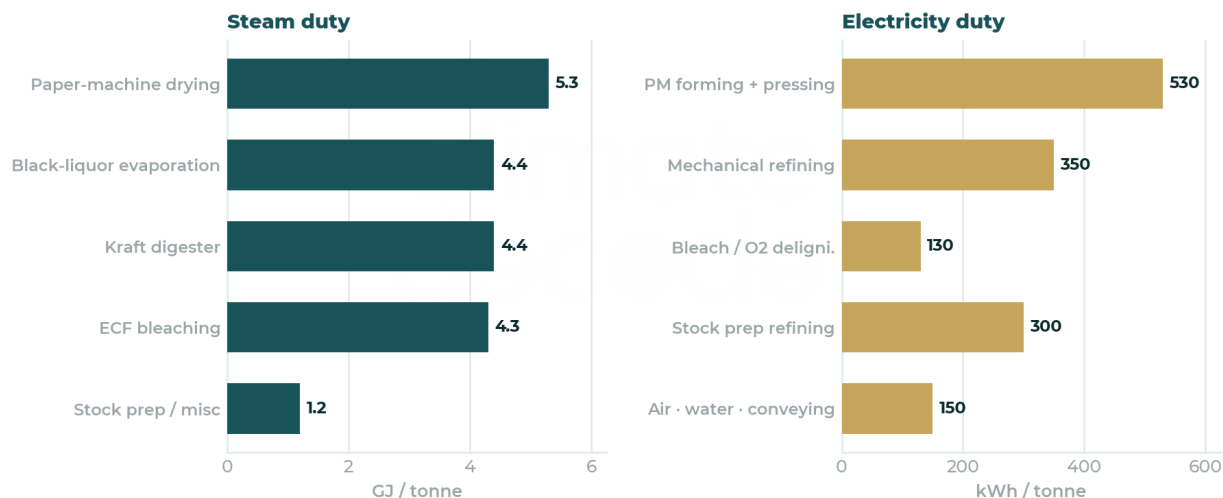


Figure 5. Per-process energy intensity profile for an integrated kraft + paper mill. Steam is dominated by paper-machine drying and black-liquor evaporation; electricity by forming and pressing, mechanical refining, and bleach-plant pumping.

The thermal fuel mix that supplies this steam load is region-specific. Canadian and Nordic mills are 70–80% biogenic, with black liquor burned in the recovery boiler, bark in the biomass boiler, and supplementary purchased biomass covering most remaining steam demand; natural-gas package boilers handle residual load, and the lime kiln burns either natural gas or heavy fuel oil. U.S. integrated kraft mills follow the same overall architecture but lean somewhat more on fossil natural gas — the American Forest & Paper Association reports an aggregate U.S. mix of approximately 60–65% biogenic, with natural gas at 25–30% of mill steam (compared with 10–15% in Canada and the Nordic region), reflecting broader pipeline access and a paper-grade product mix that includes more grades produced at non-integrated paper-only mills. This biogenic-heavy fuel base is what distinguishes pulp & paper from most other industrial sectors and explains why the sector contributes only about 2% of industrial CO₂ despite consuming 6% of industrial energy.

SECTION 03

Building a Hypothetical Mill and Identifying Its Hotspots

03

To make the emissions discussion concrete, we construct a hypothetical integrated kraft mill that closely matches the average North American facility on production scale, energy intensity, and fuel mix. This stylized mill becomes the reference case for every decarbonization lever, MAC calculation, and case study that follows. The construction proceeds in four steps: (1) define the production scale; (2) lay out the steam supply across three boilers and a direct-fuel lime kiln; (3) reconcile the electricity supply between on-site cogeneration and the grid; (4) sum the resulting emissions footprint and identify the hotspots.

3.1 Production Scale

The hypothetical mill produces 200,000 air-dried tonnes per year (ADt/yr) of bleached kraft pulp, with an integrated paper machine converting most of the pulp on-site into fine paper or linerboard. This sits at the median of operating North American kraft mills — large enough to be representative but small enough that capital decisions at this scale are typical of the broader sector. Total final energy demand at this output level is approximately 2.2 million GJ/yr of process steam (delivered at ~11 GJ/ADt) and 158 GWh/yr of electricity (~790 kWh/ADt), consistent with the energy-intensity envelope established in Section 2.5.

3.2 Steam Supply — Three Boilers Plus the Lime Kiln

Mill steam is supplied by three boilers operating in parallel, each contributing a share of the total demand. The chemical recovery boiler is the workhorse: it burns concentrated black liquor — the spent cooking liquor from the kraft digester — and delivers approximately half of all mill steam at zero fossil-fuel cost, since black liquor is a biogenic by-product of pulping itself. The bark and biomass boiler contributes a further fifth, fuelled by the bark stripped at the wood yard plus supplementary purchased biomass. The remaining ~28% of demand is met by a natural-gas package boiler that fills the residual gap and provides operational flexibility. The lime kiln, although not a steam producer, is the fourth combustion source: it calcines spent calcium carbonate back to calcium oxide at ~1,200 °C and consumes NG directly. Two observations follow: biogenic combustion (recovery + biomass boilers) supplies 72% of mill steam — the source of the sector's distinctive low fossil-emission profile despite high energy intensity — while fossil natural gas appears at two distinct sources, the NG package boiler and the lime kiln, which together account for the bulk of mill Scope-1 fossil emissions.

TABLE 3

Steam and direct-fuel sources at the hypothetical 200 kADt/yr integrated kraft mill.

Source	Fuel	Steam share	Steam output (GJ/yr)	CO ₂ (tCO ₂ /yr)	Classification
Recovery boiler	Black liquor	50%	1,100,000	~220,000	Biogenic
Bark / biomass boiler	Bark + biomass	22%	480,000	~60,000	Biogenic
NG package boiler	Natural gas	28%	620,000	~36,000	Fossil Scope 1
Lime kiln (direct fuel)	Natural gas	n/a	n/a	~33,000	Fossil Scope 1
Mobile equipment	Diesel	n/a	n/a	~2,300	Fossil Scope 1

3.3 Electricity Supply — Cogeneration Plus the Grid

The mill's 158 GWh/yr electricity demand is met from two streams. On-site combined-heat-and-power (CHP) cogeneration extracts electricity from high-pressure steam produced by the recovery and biomass boilers as that steam expands through back-pressure turbines on its way to process duty. At our hypothetical mill, cogeneration delivers approximately 60 GWh/yr — about 40% of mill demand — and because the cogeneration header is fed exclusively by the biogenic boilers, the on-site emission profile of this stream is biogenic. The natural-gas package boiler does not drive the cogeneration turbine in this configuration; its role is to top up the medium- and low-pressure process header during peak demand and biogenic-boiler outages. The remaining ~100 GWh/yr of mill demand is purchased from the grid, carrying a Scope-2 emission factor that varies enormously by jurisdiction. Using Environment and Climate Change Canada's 2026 consumption-intensity reference values, Quebec sits at roughly 2 kg CO₂e/MWh, Manitoba at about 3, Newfoundland and Labrador at about 17, and British Columbia at about 18 — all hydropower- or hydro-and-wind-dominated grids. Ontario has risen to roughly 59 kg CO₂e/MWh as gas plants pick up more of the post-coal peak load (up from about 30 in 2023). Alberta sits at approximately 438 kg CO₂e/MWh as it transitions from coal to gas; Saskatchewan, still coal-heavy, sits at about 631; Nova Scotia at about 581. U.S. coal-heavy regions and grid-average North America generally sit in the 300–600 kg CO₂e/MWh band. At a Canadian grid-average factor of roughly 150 kg CO₂e/MWh, purchased electricity at our mill (~100 GWh/yr) contributes about 15 ktCO₂e/yr of Scope-2 emissions; at the Alberta factor ~44 ktCO₂e/yr; at the Saskatchewan factor about 63 ktCO₂e/yr.

Mill electricity is consumed unevenly across processes. Paper-making is by far the largest single draw at roughly 500 kWh per tonne of paper for forming, pressing, and dryer-section drives combined. Stock preparation and refining add another 200–400 kWh/t depending on the pulp blend. Pulping electricity varies sharply by route — a few hundred kWh/ADt in chemical kraft, but two to three thousand kWh/ADt in mechanical pulping where the refiners are the dominant load. Bleaching, screening, and washing across both pulping and paper lines together add 100–200 kWh/ADt. The remainder is split across compressed air, water treatment, conveying, lighting, and ventilation. Where the grid is fossil-heavy, every kilowatt-hour saved flows directly into Scope-2 reduction; where the grid is clean, the same saving has little climate impact but still cuts cost.

IN FOCUS · ENERGY DUTY

Drying — the largest single energy duty in the mill

Drying consumes about 5.3 GJ of steam per tonne of paper, marginally higher than the three other principal steam consumers — the kraft digester, ECF bleaching, and black-liquor evaporation — each of which sits at 4.3–4.4 GJ per tonne. What singles drying out as worth a dedicated treatment is the variety and maturity of available abatement options on the dryer section itself, which span low-CAPEX efficiency retrofits, commercially proven drying-technology innovations, and the most-developed industrial-heat-pump application in pulp & paper. At a 200,000 ADt/yr mill the dryer steam load is approximately one million GJ per year.

The first wave of solutions is best-available efficiency on the existing dryer. Closed dryer hoods with secondary heat recovery — capturing exhaust at 80–85 °C to pre-warm process water and ventilation supply air — are now standard on modern machines and typically recover 5–10% of the dryer thermal load. Layering a broader heat-recovery and -integration retrofit on top (a plant-wide heat-exchanger network designed using pinch analysis) has delivered an additional 7–13% steam saving in audited mills, and dedicated steam-system optimization (condensate recovery, trap maintenance, insulation, controls) has demonstrated 8–10% savings at payback under one year. Combined, these mature measures can cut dryer steam demand by 15–25% before any structural retrofit is considered.

The next lever is the shoe press. By replacing a conventional roll press with an extended-nip shoe-press configuration, the sheet's solids content leaving the press section is lifted by 2–4 percentage points. Each percentage point of dryness gained at the press section cuts drying steam by roughly 4–5%, so a typical shoe-press retrofit reduces dryer steam by 12–20%. Modern paper machines are increasingly equipped with shoe presses as standard; older machines remain a relevant retrofit target.

Beyond efficiency and pressing, three drying-technology innovations have moved beyond R&D to varying degrees of commercial maturity. Condensing-belt drying (Condebelt) is commercially proven at TRL 9, with installations running in Finland since 1996 and South Korea since 1999 delivering 10–20% steam savings; broader adoption has nonetheless been limited because the 20–40-year asset life of an existing dryer section is a slow diffusion brake. Steam/air impingement drying is at TRL 7–8 with precedents in the board and paperboard segments. Impulse drying, which combines pressing and contact heating in a single high-temperature nip (150–500 °C, ~100 ms residence), could in principle deliver 20% drying-steam savings but remains at TRL 5–6 after 25+ years of research because blistering and delamination have not yet been resolved at production scale.

Where the grid is low-carbon, the dryer is also a natural target for electrification through heat-pump retrofit. An industrial heat pump drawing waste heat from the dryer exhaust at 80–85 °C and lifting it to process-water duty at 60–95 °C delivers coefficients of performance of 4–6, with capital cost around CAD \$400–800 per kW of thermal capacity. Because these levers stack, sequencing matters: deploy mechanical-dewatering improvements first (shoe press), then thermal-side recovery, and finally electrification once the residual thermal load is small enough for the heat pump to size economically. A shoe press deployed first lowers the steam baseline against which any heat-pump retrofit is sized, reducing the heat-pump capital cost by 15–20%.

3.4 Per-Process Emissions Footprint

To prioritise decarbonisation we allocate the mill's fossil emissions back to the process steps that drive them. Each process step carries three contributions: emissions from the steam it consumes (the three boilers feed a common header, so every gigajoule of mill steam carries the same blended fossil factor of about 14 kgCO₂); emissions from the electricity it consumes (the cogen-plus-grid blended factor from §3.3); and any direct fossil emission occurring at the process itself. Biogenic CO₂ from black-liquor and biomass combustion sits outside the regulatory boundary of the industrial-emitter carbon markets and is reported separately at roughly 280,000 tCO₂/yr.

Figure 6 • Per-process fossil emissions allocation (200 kADt/yr mill)

The lime kiln (direct fuel) and the natural-gas package boiler together drive ~85% of fossil Scope-1.

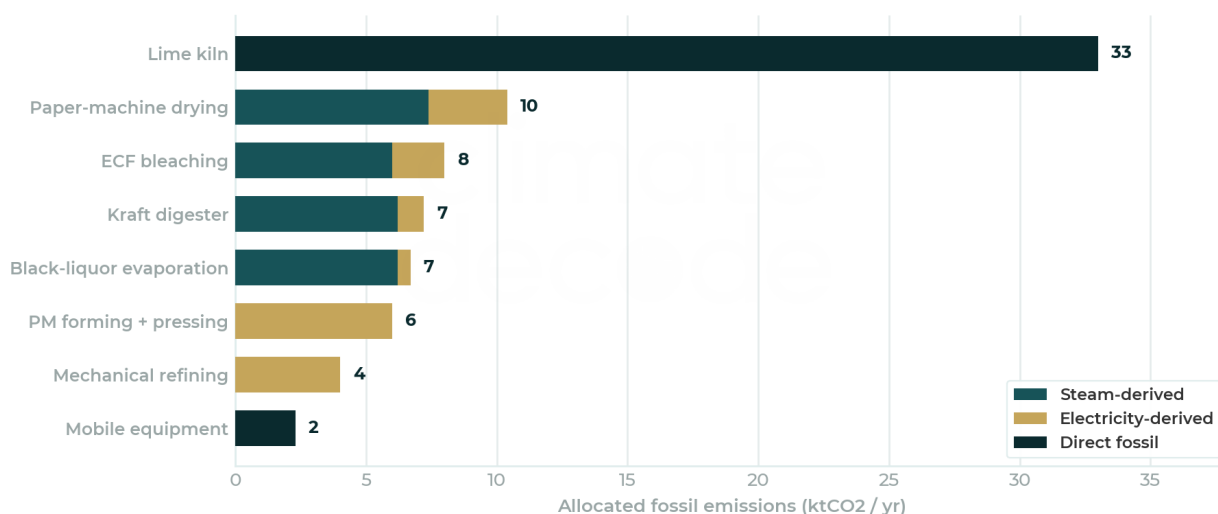


Figure 6. Per-process fossil emissions allocation at the hypothetical 200,000 ADt/yr integrated kraft mill. Process steps are ranked by total allocated fossil emissions; each bar is split into steam-derived, electricity-derived, and direct-process / direct-fuel contributions.

The priority story the chart tells is one of load relief. Every fossil tonne in the mill ultimately flows through one of two mill-level loads — boiler steam and grid electricity — plus a small standalone load at the lime kiln. Cutting steam demand at the top steam consumers (paper-machine drying, the kraft digester, ECF bleaching, black-liquor evaporation) relieves the natural-gas package boiler one-for-one: every GJ of demand that disappears at a steam hotspot frees biogenic-boiler capacity, and because the boilers are fungible at the header, that freed biogenic capacity substitutes fossil steam supplied by the NG boiler elsewhere — the fossil reduction equals the steam saved times the blended fossil factor regardless of where in the mill the saving happens. Cutting electricity demand at the largest consumers — paper-machine forming and pressing, and mechanical refining where present — reduces grid imports one-for-one and removes Scope-2 emissions at the grid factor of the local jurisdiction. The lime kiln sits outside both of these loads: its emissions are direct kiln-burner fuel plus non-combustion CO₂ from make-up calcium carbonate, and they respond to kiln-fuel and chemistry choices specific to the kiln.

SECTION 04

Decarbonization Solutions

04

Decarbonization options for the sector group into six families: energy efficiency, fuel switching, electrification, process innovation, bioenergy with carbon capture and storage, and recycled-fibre substitution. Each category is introduced briefly below; the table that follows lists the principal solutions in that category along with their description, expected emissions and energy impact, technology readiness level (TRL), and indicative MAC at the federal Canadian carbon-price schedule. Numbers are order-of-magnitude estimates that anchor the conversation; project-specific results require a site-specific model.

4.1 Energy Efficiency

Energy efficiency is the always-on first wave of decarbonization. The measures here deliver the same physical output of pulp or paper with less primary energy, and the technology is generally mature. A comprehensive efficiency programme can cut mill-wide energy demand by 15–25%, freeing thermal headroom and capital that would otherwise be needed for the more capital-intensive electrification and capture levers. Cost-effectiveness varies meaningfully by mill — the MAC notes here are directional, drawn from our model defaults and the cited literature; a site-specific MAC requires the mill's own CAPEX, energy prices, and carbon-policy stack.

TABLE 4

Energy-efficiency levers tracked in the mill model.

Solution	Description	Energy / emissions impact	TRL	MAC orientation
Energy management system + analytics	Mill-wide controls, real-time data, advanced process automation	10–15% mill-wide energy reduction	9	Strongly negative — short payback
Variable-frequency drives (VFDs)	Electronic speed control on refiners, fans, pumps replaces throttling	~10% on drives equipped; ~3.5% mill electricity overall	9	Negative — payback under 3 years
PM closed hood + heat recovery	Sealed dryer hood; exhaust pre-warms ventilation, white water, shower water	8–13% drying-section energy reduction	9	Near-zero to mildly negative
Shoe press	Extended-nip press lifts press-section dryness 2–4 pp; each pp cuts drying steam ~4–5%	12% drying-section steam; ~3% added press electricity	9	Project-specific; non-energy benefits
Heat recovery from bleach effluent	Counter-current exchangers recover heat from spent bleach filtrate	~6% bleaching-step steam reduction	9	Mildly negative

Solution	Description	Energy / emissions impact	TRL	MAC orientation
Heat recovery and integration	Plant-wide heat-exchanger network designed using pinch analysis	~20% mill-wide steam reduction (audited)	9	Strongly negative across audited mills
Steam-cycle washing (brown-stock)	Brown-stock washing on recovered evaporator condensate + steam stripping	15–25% washing thermal energy	8–9	Negative at typical scale
MVR on BL evaporators	Open-cycle compressor recycles flash steam from each evaporator effect	40–60% primary-steam reduction on evaporator train	8–9	Project-specific — negative to mildly positive
Advanced drying (Condebelt)	Condensing-belt drying replaces conventional cylinder section	10–20% drying-steam reduction	9	Positive — gated by dryer-replacement window
Membrane concentration of black liquor	Membrane pre-concentration upstream of multi-effect evaporators	5–15% evaporator steam reduction	6–7	Positive — membrane-area OPEX bound

4.2 Fuel Switching

Fuel switching replaces fossil natural gas and heavy fuel oil with lower-carbon energy carriers that integrate with existing combustion equipment. The most relevant options for pulp & paper are renewable natural gas, low-carbon hydrogen, biomass gasification, and pulverized biomass — each targeting either the lime-kiln burner or the natural-gas package boiler. The economics depend heavily on the price premium of the alternative fuel and on the carbon-policy revenue (compliance, fuel-side credits) the project can capture.

TABLE 5

Fuel-switching levers for lime kiln and natural-gas package boiler duty.

Solution	Description	Energy / emissions impact	TRL	MAC orientation
RNG — pipeline purchase	Pipeline-quality biomethane displacing fossil NG in boilers, kilns, dryers	60–90% fuel-lifecycle CO ₂ reduction by pathway CI	9	Positive without CFR; net-negative with CFR Gaseous Class credits
On-site biogas (sludge)	Anaerobic digestion of mill organics; biogas combusted on-site	Displaces fossil NG; generates CFR Gaseous Class credits	9	Strongly negative with CFR; positive without
Low-carbon hydrogen (purchased)	H ₂ combustion in modified lime-kiln burner / dual-fuel boiler	100% fuel-side decarbonization on duty served	5–7	Positive — high; compliance revenue narrows gap
Biomass gasification (lime kiln)	Wood waste gasified to syngas firing the lime kiln (60–100% NG displacement)	Eliminates lime-kiln fossil emissions	8	Positive — moderate; compliance revenue narrows gap
Pulverized biomass (kiln fuel)	Wood dried, milled, injected into the lime-kiln burner	Same fossil-CO ₂ reduction as gasification at lower CAPEX	7	Positive — lower than gasification
LignoBoost lignin extraction	Lignin precipitated from black liquor before recovery boiler; burned or sold	~20% lime-cycle load reduction; product revenue \$300–500/t	9	Negative when lignin sold at market price

4.3 Electrification

Electrification replaces direct fossil combustion with electricity. Where the grid is low-carbon (Quebec, British Columbia, Sweden, Norway) the abatement is near-complete; where the grid is fossil-heavy, electrification only shifts emissions from Scope 1 to Scope 2. Two options dominate practical deployment in pulp & paper: industrial heat pumps and electric boilers. Electric boilers are operationally the most straightforward retrofit but carry meaningful capital cost and an operating-cost profile that depends heavily on the local electricity price; heat pumps deliver a higher coefficient of performance and tend to be the lower-cost option per tonne of CO₂ abated where the duty fits their temperature envelope. Mechanical vapour recompression (MVR) on the black-liquor evaporator train is sometimes counted here because it substitutes electricity for steam — we have treated it under §4.1 Energy Efficiency, where it is conventionally classified.

IN FOCUS · ELECTRIFICATION

Heat pumps — the centre of most mill electrification plans

In simple terms, a heat pump moves heat from a low-temperature waste stream to a higher-temperature process duty, using electricity instead of fuel. Its efficiency is described by a coefficient of performance (COP): at COP 4, each kilowatt-hour of electricity delivers four kilowatt-hours of useful heat. The same principle as a refrigerator, run in reverse.

Pulp & paper mills are well-matched to heat-pump deployment for two reasons: most of the sector's thermal demand sits at moderate temperatures (below ~175 °C), and mills have a steady supply of warm waste streams — dryer exhaust, evaporator condensate, bleach-plant filtrate — that are otherwise rejected to atmosphere or cooling water. The combination of low-temperature demand and abundant waste heat makes the sector one of the highest-leverage industrial categories for heat-pump deployment.

Where heat pumps fit. The most-deployed application today is paper-machine wet-end and shower-water pre-heating, where the temperature lift is modest and COPs in the 4–6 range are routine. Higher-temperature applications — heat pumps that produce low- or mid-pressure steam directly — are more recent and have reached commercial scale in the past few years; COPs drop to roughly 2.5–3.5 at these duties, but the technology now works.

On the economics, capital cost ranges roughly CAD \$400–1,200 per kW of thermal capacity — the lower end for simple low-temperature retrofits, the upper end for high-temperature steam-raising units. Two variables drive the project case: the local electricity-to-NG price ratio, and the grid emission factor. In jurisdictions with low-carbon, competitively-priced electricity (Quebec, British Columbia, Norway, Sweden), heat pumps reach negative MAC once compliance carbon revenue is layered. In jurisdictions with fossil-heavy or expensive electricity, the same retrofit may not clear the bar even before considering Scope-2 emissions.

What we watch for in diligence. In brownfield retrofits the integration infrastructure (piping, heat-exchanger network, controls, building modifications) routinely dominates total CAPEX, not the heat-pump unit itself. The steam–electricity coupling also matters: reducing package-boiler steam through a heat pump cuts back-pressure-turbine cogeneration, which increases grid imports and modifies the project's Scope-2 footprint. Both effects need to be modelled before signing off.

Where the sector is going. Industrial heat-pump capacity in pulp & paper is expected to roughly triple between 2024 and 2030 across IEA Net Zero and Stated Policies scenarios. A reference point: in 2023 a European pulp & paper company contracted a 12 MW thermal heat-pump-plus-mechanical-vapour-compressor system that lifts waste heat at 10–20 °C to 170 °C process steam, powered by renewable electricity — currently the most-cited commercial reference for high-temperature dryer-side electrification.

TABLE 6

Electrification levers — heat pumps and electric boilers.

Solution	Description	Energy / emissions impact	TRL	MAC orientation
Heat pump (low-temp, <=90 °C)	Recovers waste heat from dryer exhaust, condensate, or bleach effluent	Replaces ~0.5–1.5 GJ/ADt of NG heat; near-zero on clean grids	9	Grid-dependent — negative on clean grids
Heat pump (high-temp, 110–175 °C)	Delivers LP/MP steam directly via natural-refrigerant compressors	Replaces ~1.0–2.5 GJ/ADt of NG steam	7–8	Positive — lower on clean grids with credits
Electric boiler	Direct conversion of electricity to steam; a straightforward boiler swap	100% Scope-1 elimination on duty served; Scope-2 follows grid	9	Highly grid-and-tariff-dependent

4.4 Process Innovation

Process innovation refers to retrofits or replacements of core unit operations that fundamentally change how pulp is made. The two near-commercial options for kraft are black-liquor gasification (replacing the recovery boiler) and borate auto-causticizing (reducing or eliminating the lime kiln). Both are end-of-life replacement decisions — they make economic sense only when the equipment they displace is approaching retirement, which is why the MAC orientation here reads positive on a stand-alone basis but improves materially once the avoided-CAPEX of the equipment being replaced is netted against the project.

TABLE 7

Process-innovation levers — end-of-life replacements for the recovery boiler and lime kiln.

Solution	Description	Energy / emissions impact	TRL	MAC orientation
Black-liquor gasification (BLG)	High-pressure gasifier + combined cycle replaces Tomlinson boiler; opens FT-fuel / methanol revenue	+40–60% electricity per tonne BL; biofuel revenue	6–7	Positive — gated by recovery-boiler cycle; forecloses BECCS at same stack
Borate auto-causticizing (Neobor)	Sodium tetraborate substitutes for calcium loop in causticizing; cuts lime-kiln duty	20–60% lime-kiln duty reduction by substitution rate	7	Positive — gated by lime-kiln replacement window

4.5 Bioenergy with Carbon Capture and Storage (BECCS)

BECCS is post-combustion separation of CO₂ from biogenic flue-gas streams (recovery boiler, biomass boiler), followed by compression, pipeline transport, and geological storage. Because the captured carbon is biogenic, BECCS produces verified negative emissions — the most valuable carbon-credit type on voluntary markets. Compliance markets do not credit biogenic captures, so BECCS economics depend on the combination of tax credits (for example CCUS ITC) and voluntary-removal-credit offtakes.

Detailed case-study economics are in §5.6.

TABLE 8

Bioenergy with carbon capture and storage (BECCS) at the recovery and biomass boilers.

Solution	Description	Energy / emissions impact	TRL	MAC orientation
BECCS — post-combustion amine	Amine absorption on RB + biomass-boiler stack; compression + pipeline + saline storage	Verified negative emissions; ~40 ktCO ₂ /yr captured at hypothetical mill	8 (post-comb), 5 (pre-comb)	Strongly positive on plain MAC; near-zero / net-negative with 50% CCUS ITC + VCM offtake at ~CAD \$275/tCO ₂

4.6 Recycled-Fibre Substitution and Circularity

Recycled fibre is the lowest-energy fibre input in the sector. Each 10-percentage-point shift toward recycled fibre at an integrated mill cuts roughly 1.4 GJ of total energy and 0.07 tCO₂ of fossil emissions per tonne of pulp by displacing the most energy-intensive virgin-pulping steps. A 200 kADt mill shifting from 0% to 30% recycled fibre saves around 84,000 GJ and 4,200 tCO₂ per year. RCF deployment is bounded by fibre-quality limits and by feedstock-collection logistics.

TABLE 9

Recycled-fibre substitution and circularity levers.

Solution	Description	Energy / emissions impact	TRL	MAC orientation
RCF substitution (10–30 pp)	Replace virgin-pulp share with recovered paper; skip cooking, evaporation, recovery boiler, lime kiln	–1.4 GJ/ADt and –0.07 tCO ₂ /ADt per 10 pp	9	Negative at typical NA fibre prices; furnish-quality bound
Heat-to-district-heating	Export low-grade waste heat (70–90 °C) to municipal networks	5–10% reduction in flue-gas heat loss; \$3–8/GJ revenue	9	Negative where an offtaker exists
Biorefinery — tall oil + turpentine	Recovery and sale of kraft cooking co-products	Operating-margin uplift \$20–60/ADt at commercial prices	9	Negative — revenue-positive in liquid markets

IN FOCUS · CIRCULARITY

Circularity — closing the system

Circularity is the discipline of designing the mill so every output stream becomes either a saleable product or a feedstock for another mill process. The opposite of a linear take-make-dispose flow, it is the design lens through which several of the levers in this section reinforce one another and through which most of the highest-leverage decarbonization moves at a mill are best understood.

The kraft chemical recovery cycle is the textbook example. Spent cooking liquor — the black liquor extracted from the digester — is concentrated in evaporators, burned in the recovery boiler to produce roughly half of mill steam, and the inorganic chemicals are recovered as a smelt that is causticized back to fresh white liquor for re-use. The same stream that would otherwise be a major liquid waste closes two loops at once: the chemical loop (98% of cooking chemicals recovered) and the energy loop (lignin combustion makes the kraft mill close to energy self-sufficient).

On-site biogas production extends the same logic to wastewater and sludge. Anaerobic digestion of mill primary and biological sludge produces biogas that displaces fossil natural gas in the package boiler or lime kiln; what was previously a sludge-disposal cost becomes a fuel input. The same digester also closes a methane loop, capturing fugitive methane that would otherwise leave the mill's wastewater treatment.

Recycled-fibre substitution closes the loop on the product itself. Each percentage point of recycled fibre is a percentage point of recovered paper diverted from landfill, treated as a feedstock rather than a waste. Heat recovery and integration does the same for thermal energy: dryer exhaust at 80–85 °C, bleach effluent at 50–70 °C, and evaporator condensate at 60–95 °C are progressively returned to process duty through exchanger networks designed using pinch analysis. Several Nordic mills export low-grade waste heat to municipal district-heating networks at 70–90 °C, earning a stable \$3–8/GJ of revenue.

Pulled together, these moves describe the biorefinery vision: a mill that recovers chemicals, energy, fibre, heat, and CO₂ from every internal stream and operates as a multi-product facility rather than a single-product manufacturer. Industry roadmaps project \$20–60 per ADt of operating-margin uplift by 2040 from the combined suite — lignin extraction at \$300–500/t, tall oil at \$700–1,100/t, turpentine at \$1,500–2,500/t, cellulose nanofibres, on-site biogas, and waste-heat exports. The closing-the-system framing turns these revenue streams from incremental add-ons into a structurally more resilient mill business model.

4.7 Innovative Solutions — The Pre-Commercial Pipeline (TRL 2–6)

Beyond the commercial and near-commercial levers above, a pipeline of pre-commercial technologies could materially reshape the sector's energy and emissions profile over the next 10–15 years if they reach commercial scale. The candidates listed below are TRL 2–6 today — laboratory or pilot demonstrations. They are not investable today; they are part of the medium-term watchlist for capital planning.

TABLE 10

Pre-commercial pipeline of TRL 2–6 candidates — medium-term watchlist for capital planning.

Technology	Concept	Energy / abatement impact	TRL
Microwave pre-treatment	Microwave heating of wood chips before kraft cooking — softens lignin	20–40% NG reduction at digester	4–6
Deep eutectic solvent (DES) pulping	Low-temperature DES replaces NaOH/Na ₂ S cooking — eliminates kraft chemistry	30–50% energy; eliminates lime cycle	3–4

Technology	Concept	Energy / abatement impact	TRL
Enzymatic pre-treatment	Cellulase / xylanase pre-treatment lowers refining and bleach demand	10–25% mech-pulp refining electricity; 5–15% bleach chemicals	4–5
Electric digester	Resistance / induction heating of cooking liquor — eliminates digester steam	Replaces 2.1 GJ/t steam with electricity	3–4
Plasma-assisted bleaching	Non-thermal plasma generates oxidants in-situ — reduces ClO_2 and H_2O_2	30–60% bleach chemical reduction	2–3
Electric calcination	Direct electric heating of CaCO_3 to CaO in lime kiln	100% fuel-side decarbonization of lime kiln	3–4
Black-liquor electrolysis	Electrochemical recovery of caustic — H_2 by-product, eliminates RB combustion	30–60% reduction in BL combustion CO_2	2–3
Functional surface treatments	Surface coatings + bulk-density reduction (lightweighting)	8–18% raw-material + drying-energy reduction	4–5
Laser ultrasonic stiffness sensing	Real-time fibre-stiffness measurement for closed-loop refining/pressing	3–8% PM electricity + drying steam savings	5–6
Boost dryer (board / packaging)	High-temperature impingement drying — eliminates steam-cylinder section	20–40% drying-section steam reduction	5–6
Aq-Vane stratified forming	Multi-jet stratified-furnish PM forming section	10–20% PM electricity + dewatering improvement	4–5
Impulse drying	Combined press + heat impulse — replaces press + early dryer cans	15–25% paper-machine drying steam	5–6

These candidates share three characteristics: low TRL today (substantial pilot-to-commercial scale-up required over 5–15 years); potentially transformative impact on either energy demand or emission profile if successful; and high R&D risk with limited near-term commercial deployment. Mills should not commit capital to these solutions today, but should track pilot-scale developments and reserve capital flexibility for the second half of the 2030s. The next decade's decarbonization will be commercial-scale deployment of mature levers; the decade after that will hinge on which TRL-2-to-6 innovations make it through the pilot phase.

4.8 Interrelations and Sequencing — Why Order Matters

The six lever families in §4 do not operate independently. Many levers compete for the same energy stream, share common infrastructure, or change the size and economics of the next lever in line. Choosing what to deploy and in what order is as important as choosing which technology to deploy at all. A few of the most consequential interrelations:

Heat pumps versus cogeneration. A heat-pump retrofit that displaces NG package boiler steam also reduces the cogeneration stream (because steam flow through the back-pressure turbine drops). The mill imports more grid electricity to compensate, which adds Scope-2 emissions in jurisdictions with high grid carbon intensity. A heat pump that looks attractive in Quebec or BC (clean grid) can be net-emissions-positive in Alberta. Always model the steam-electricity coupling explicitly.

Energy efficiency before electrification. Paper-machine closed hoods, shoe presses, and heat recovery and integration retrofits all reduce the steam load on the boilers. If these are deployed first, downstream electrification (heat pumps, electric boilers) can be sized smaller — saving 15–25% of the electrification CAPEX. Reversed sequencing forces over-sized electric capacity that runs at part-load, hurting the economics of both layers.

LignoBoost and lime-kiln decarbonization. LignoBoost extracts ~10–15% of black-liquor lignin before the recovery boiler. Less organic matter in the recovery boiler produces less Na_2CO_3 in the smelt, which lowers the causticizing load, which lowers the volume of lime mud sent to the kiln. Commercial LignoBoost installations indicate roughly a 15–25% reduction in lime-kiln duty. A kiln retrofit sized after LignoBoost is therefore meaningfully smaller and cheaper than one sized before.

BLG forecloses BECCS at the recovery boiler. Black-liquor gasification replaces the Tomlinson recovery boiler with a high-pressure gasifier producing syngas. That eliminates the recovery-boiler flue-gas stack — and with it, the largest biogenic CO_2 stream available for BECCS. A mill considering both must choose: stay with the recovery boiler and pursue BECCS, or convert to BLG and access biofuel revenue instead. Both are good options; both cannot be deployed at the same site.

BECCS adds steam parasitic load. Amine regeneration consumes 3.5 GJ of steam per tonne of CO_2 captured. At 40 ktCO_2/yr capture, that is 140,000 GJ/yr of additional steam demand — roughly 6% of the mill's total steam. If this comes from the existing NG package boiler, the parasitic steam adds fossil emissions that partly offset the biogenic capture. The right pairing is BECCS plus a biomass-boiler expansion, or BECCS deployed only after EE measures have freed enough biogenic steam capacity to absorb the regeneration load.

RNG / biogas competes with electric boilers for the residual NG load. Both levers target the same fossil natural-gas duty. Deploying one reduces the addressable abatement of the other. Mill operators must pick the better-NPV lever for their fuel-price + carbon-policy environment, not assume both can stack.

Recycled fibre shifts the decarbonization calculus. Each 10-pp shift toward RCF cuts cooking, evaporation, and lime-kiln duty by roughly the same proportion. After a major RCF expansion, the lime kiln may shrink to the point where small-scale CCS is uneconomic — but the same expansion frees biogenic-fuel capacity for BECCS at the bark boiler. RCF is therefore both a direct lever and a sequencing variable for the rest of the portfolio.

The optimal sequence

Deploy energy efficiency first (frees thermal headroom), then RCF where fibre quality permits (resets the demand baseline), then electrification on the residual load, then BECCS or BLG once the steam-electricity- CO_2 ledger is balanced. Reversing this sequence regularly leaves 15–30% of cost-effective abatement on the table.

IN FOCUS · DEPLOYMENT

Challenges to deployment

Six interlocking barriers shape every mill-level capital decision in this sector. They are not independent — capital, policy, technology, and market access each amplify the others — and a coherent decarbonization plan has to address them together rather than one at a time.

- **Upfront capital.** A high-efficiency recovery-boiler retrofit at a linerboard mill has been costed at USD \$256 million, on top of the greenfield \$1–2 billion price tag for a modern 500 kADt mill. Asset lives of 30–50 years mean replacement decisions cluster on long cycles, and decarbonization economics tighten materially outside the natural replacement window.
- **Fuel-switching cost gap.** Green hydrogen production currently sits at roughly USD \$4–6/kg, projected to fall toward \$2/kg by 2030 — but even at \$2/kg the energy-equivalent cost is ~\$15–20/GJ, several times pipeline natural gas. The implied abatement cost is well above \$200/tCO₂ before any policy support; the U.S. §45V credit (up to \$3/kg) and Canadian Clean Hydrogen ITC (up to 40% of CAPEX) can close most of that gap, but bankability is tied to incentive durability over a 10-to-15-year offtake horizon.
- **Policy support.** The policy stack is uneven: some jurisdictions carry a complete set (Canada and parts of the EU), some partial (the U.S., via 45Q and 45V but no nationwide carbon price), and many regions none at all. Step-down schedules sit inside the investment window — the Canadian CCUS ITC halves after 2030, U.S. §45Q crediting runs 12 years from in-service. The same physical retrofit can be bankable in one geography and uneconomic in another for purely policy reasons.
- **Carbon-market uncertainty.** Forward curves for EU ETS, WCI, and federal OBPS have shown wide swings; Canadian compliance prices are scheduled to CAD \$170/tCO₂ by 2030 but post-2030 levels are unset; the EU ETS has cycled between roughly €60 and €100/tCO₂. The voluntary removal-credit market is narrow on the demand side, so project finance for any removal-dependent project (BECCS in particular) depends on securing a long-dated offtake with a creditworthy counterparty before the project is built.
- **Technology readiness and reliability.** Many of the highest-impact levers — BECCS, BLG, high-temperature heat pumps above 130 °C, hydrogen combustion in lime kilns — sit at TRL 6–8 today. A first-of-a-kind installation carries integration, performance-warranty, and operational-reliability risk that mature technologies do not, and these risks compound with the long asset life.
- **Workforce availability.** A mill that retrofits a heat pump, a biomass gasifier, or an amine-capture system needs engineers, operators, and maintenance technicians qualified to run the new equipment. The talent pool is small relative to the deployment trajectory implied by sector net-zero plans, and the lead time to train it is on the order of five to ten years.

SECTION 05

Carbon Markets, Tax Incentives, and the Cost of Carbon

05

5.1 The Global State of Carbon Pricing

Carbon pricing is now the most widely deployed economic instrument in industrial decarbonization. Coverage has expanded materially over the past decade, and for most pulp & paper mills in North America and Europe a carbon price already applies. The relevant question for mill operators is no longer whether emissions will be priced but how the layered combination of compliance prices, tax credits, and fuel-side credits stacks at a given site. Voluntary carbon markets sit alongside this stack as a separate revenue channel — relevant for biogenic removals that compliance regimes do not credit — and are addressed separately in §5.3.

BY THE NUMBERS · 2025

Carbon pricing in 2025 — key numbers

- 80 carbon-pricing instruments operating worldwide (emissions trading systems plus carbon taxes), a net increase of five over the past twelve months.
- Approximately 28% of global greenhouse-gas emissions covered by a direct carbon price, up from roughly 5% in 2005 and 24% in 2024.
- Economies representing nearly two-thirds of global GDP have implemented either an ETS or a carbon tax. China's national ETS expanded into industrial sectors in 2024–25, bringing roughly 3 gigatonnes of additional emissions under coverage; Brazil, India, and Türkiye have met implementation milestones for new ETS launches.
- Carbon-pricing revenue exceeded USD \$100 billion globally for the second consecutive year in 2024; over half of that revenue is earmarked for environmental, infrastructure, and development programs.

5.2 Compliance Carbon Markets for Industrial Emitters

Compliance markets in the jurisdictions relevant to pulp & paper price fossil-CO₂ emissions in one of two ways. Output-based pricing systems set an intensity benchmark per unit of production: emissions above the benchmark are charged at the prevailing carbon price, and emissions below the benchmark earn tradeable credits. Cap-and-trade systems set a hard cap on total emissions and allocate or auction allowances within that cap. Both designs produce the same economic effect at the project level — each tonne of fossil abatement is worth the prevailing carbon price — but the price level varies materially by regime. Compliance regimes price fossil emissions only: biogenic CO₂ from black-liquor or biomass combustion is outside the regulatory boundary in OBPS, EU ETS, California Cap and Invest, UK ETS, and China's national ETS, and biogenic-CO₂ capture (BECCS) does not earn compliance credits. This is the structural reason BECCS economics depend on tax credits and voluntary removal markets rather than the compliance carbon price. This paper uses the Canadian federal OBPS carbon-price schedule unless

stated otherwise: \$65 (2023) to \$80 (2024) to \$95 (2025) to \$110 (2026, our case-study year) to \$125, \$140, \$155, and \$170 (2030, the legislated ceiling).

TABLE 11

Compliance carbon prices across major jurisdictions relevant to pulp & paper.

Jurisdiction	Compliance regime	2026 price	2030 trajectory
Canada — federal	Output-Based Pricing System (OBPS)	CAD \$110/t	CAD \$170/t scheduled
Ontario, AB, BC, SK	Provincial OBPS-equivalents	CAD \$110/t	Aligned with federal
Quebec	Cap-and-trade (linked WCI)	CAD ~\$45/t	Tightening cap to 2030
California	Cap-and-trade (linked WCI)	USD ~\$35/t	Tightening cap to 2030
Washington	Cap-and-trade	USD ~\$35/t	WCI linkage in process
EU ETS	Cap-and-trade (Phase 4)	€75–95/t	Tightening to 2030
UK ETS	Cap-and-trade	£40–55/t	Aligned with EU
China national ETS	Cap-and-trade	RMB 80–100/t	Coverage expanding

A 30,000 tCO₂/yr fossil-abatement project at the 2026 federal OBPS price of CAD \$110/t generates CAD \$3.3M/yr of compliance revenue — enough to move many efficiency and electrification levers from the shelf into committed capital.

5.3 Voluntary Carbon Markets and Removal Credits

The voluntary carbon market is a separate revenue channel that prices abatement and removals outside any compliance regime. Buyers are corporate purchasers using credits to meet voluntary climate commitments rather than regulated emitters meeting a compliance obligation. For pulp & paper, the VCM matters in one specific way: biogenic-CO₂ capture (BECCS) is excluded from compliance markets but can be sold as a verified removal credit on the VCM. Without that channel, BECCS at the recovery or biomass boiler has no revenue line at all. Engineered durable removals — BECCS, direct air capture, mineralization — trade in long-dated offtake markets at roughly CAD \$250–500/tCO₂eq, with ICVCM Core Carbon Principles eligibility increasingly required. Improved Forest Management trades at roughly \$10–30/tCO₂; avoided-methane projects from mill wastewater anaerobic digestion at roughly \$10–25/tCO₂. The structural risk on the VCM side is on the demand line, not the supply line: the durable-removal segment is anchored by a small number of corporate buyers, offtake contracts are bespoke, and the market is not yet deep enough to absorb the removal volumes the sector could in principle supply. Any project whose economics depend on VCM revenue must secure a long-dated offtake with a creditworthy counterparty before construction — a financing structure analogous to a power-purchase agreement, applied to removal credits.

5.4 Tax Incentives — Carbon Capture and Hydrogen

Beyond carbon markets, two families of tax-credit regimes directly subsidize the most capital-intensive decarbonization technologies in pulp & paper: CCUS, and low-carbon hydrogen. Both regimes are designed to absorb a meaningful share of upfront CAPEX. The four programmes that matter — U.S. Section 45Q and the Canadian CCUS ITC on the capture side; U.S. Section 45V and the Canadian Clean Hydrogen ITC on the hydrogen side — are summarised below.

TABLE 12

CCUS and clean-hydrogen tax-credit programmes — U.S. and Canada.

Programme	Form	Headline rate / value	Crediting period	Refundable / transferable
U.S. §45Q (CCUS)	Per-tonne tax credit	\$85/tCO ₂ saline · \$60 EOR · DAC \$180 saline / \$130 EOR	12 yrs from in-service	Transferable + refundable post-IRA; construction by Jan 1, 2033
Canadian CCUS ITC	Refundable ITC on CAPEX	50% capture · 37.5% transport & storage · 60% DAC	Single-shot at commissioning	Refundable; full 2022–2030, halved 2031–2040
U.S. §45V (Hydrogen)	Per-kg production tax credit	\$3.00/kg @ <0.45 · \$1.00 @ 0.45–1.5 · \$0.75 @ 1.5–2.5 · \$0.60 @ 2.5–4.0	10 yrs from commissioning	Transferable
Canadian Clean Hydrogen ITC	Refundable ITC on CAPEX	40% @ <0.75 · 25% @ 0.75–2.0 · 15% @ 2.0–4.0 (kgCO ₂ eq/kg)	Single-shot at commissioning	Refundable; full to 2034, halved 2035–2040

The two regimes have structurally different economic profiles. The U.S. credits are per-unit-of-output annuities over 10–12 years, most bankable where long-term production volume can be locked in. The Canadian credits are one-time refundable investment tax credits at commissioning, more useful where capital is the binding constraint and the sponsor needs to monetize at the start. The Canadian credits are refundable — the federal government pays the unused portion as cash; the U.S. credits are transferable — a sponsor that cannot use the credit against its own taxes can sell it to a third party. The timing of the step-downs is decisive: the date a project commits construction — not the date it commissions — is what locks the rate. The window to qualify at full rate is six to nine years from today, and slipping past it can materially compress project IRR even if all other assumptions hold.

5.5 CFR — Tradeable Credits for Low-Carbon Fuels

Canada's Clean Fuel Regulations (in force July 2023) create a tradeable credit market for low-carbon-fuel production. The mechanism relevant to pulp & paper is the Gaseous Class — credits generated when biogas, RNG, or hydrogen displace fossil natural gas. One CFR credit represents one tonne of CO₂-equivalent reduction; the credit currently trades at approximately CAD \$400/tCO₂e. Under Section 95 of the CFR, credits (tCO₂e) = (CI_{ref} – CI_{fuel}) × Energy Supplied (MJ) × 10, where CI_{ref} = 67.8 gCO₂e/MJ is the federal reference for natural gas, CI_{fuel} is the verified lifecycle carbon intensity of the project's pathway, and Energy Supplied is the metered fuel volume. The lower the project's verified CI, the more credits per unit of fuel delivered.

TABLE 13

Clean Fuel Regulations Gaseous Class — derived revenue per GJ of biogas by lifecycle CI pathway (at CAD \$400/tCO₂e).

CI scenario	CI _{fuel} (gCO ₂ e/MJ)	Differential (g/MJ)	tCO ₂ e / GJ	CAD revenue / GJ
Facility-specific (typical kraft mill)	22.0	45.8	0.0458	\$18.32
Optimised (avoided landfill methane)	–15.0	82.8	0.0828	\$33.12
Deep optimised (avoided manure methane)	–150.0	217.8	0.2178	\$87.12

The CI of the registered pathway is the central project-economics lever — even more impactful than the credit price itself, which can drift but does not change the number of credits the project generates per unit of fuel once the CI is locked. A facility-specific lifecycle pathway can earn about \$18/GJ; optimised pathways with avoided-methane credit can reach \$33–87/GJ. CFR also permits on-site use, where a producer consumes its own biogas in the mill to displace fossil NG — the simplest entry point, with no upgrading capital, pipeline interconnect, or marketing infrastructure.

5.6 Cost-of-Carbon Case Study #1 — BECCS at the Recovery + Biomass Boilers

This case study quantifies the MAC for installing post-combustion amine capture on the biogenic flue-gas streams of the hypothetical 200,000 ADt/yr integrated kraft mill described in Section 3. The capture target is the combined recovery-boiler and bark/biomass-boiler stack, which together emit approximately 280,000 tCO₂/yr of biogenic CO₂. At an 85% capture rate, the project removes 40,000 tCO₂/yr of biogenic CO₂; the figure reflects a partial-stream early-deployment configuration, with full-stream capture at 224,000 tCO₂/yr feasible at similar unit cost but roughly double the upfront capital.

5.6.1 Inputs and key assumptions

TABLE 14

Case Study #1 — BECCS at the recovery and biomass boilers. Key inputs and assumptions.

Parameter	Value	Unit	Source / note
Captured biogenic CO ₂	40,000	tCO ₂ /yr	85% capture; partial-stream configuration
Unit CAPEX	1,500	CAD/tCO ₂ -yr capacity	Industry-typical post-combustion benchmark
Unit OPEX	90	CAD/tCO ₂	Amine make-up + transport + storage + labour
Parasitic electricity	0.35	MWh/tCO ₂	Capture + compression
Parasitic steam (NG boiler)	3.5	GJ/tCO ₂	Amine regeneration
Project life	20	years	Standard for industrial CCS
Discount rate	15	%	Industrial hurdle rate
Canadian CCUS ITC	50	% of CAPEX	Federal — refundable, full rate to 2030
VCM removal-credit price	275	CAD/tCO ₂ eq	Engineered biogenic removal — Puro.earth, Microsoft Frontier
Federal OBPS price (2026)	110	CAD/tCO ₂	Canadian federal schedule

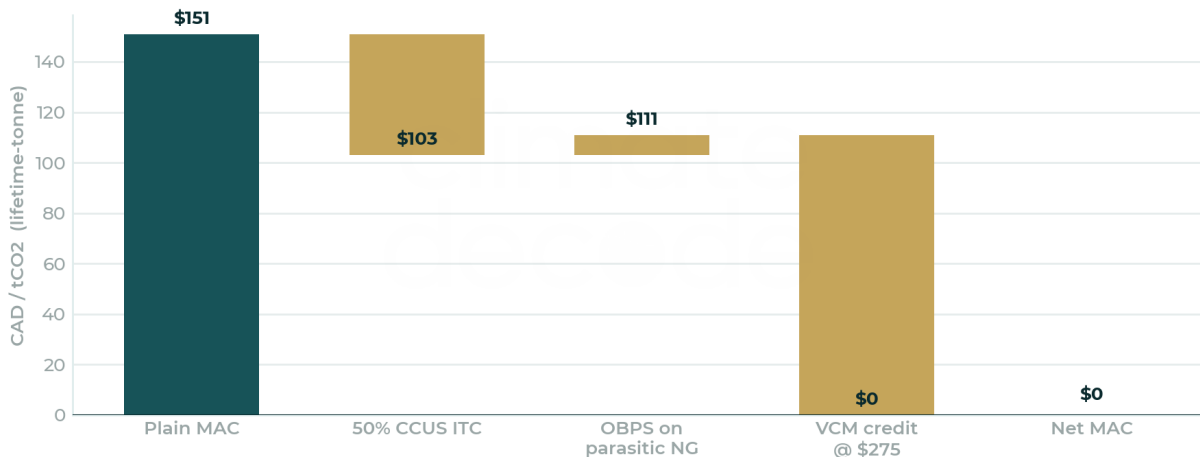
5.6.2 Layered MAC build-up

We start with a plain marginal abatement cost — capital and operating cost only, no incentives, no carbon-market revenue. We then layer the ITC (which reduces capital cost), then the OBPS effect on parasitic NG (a small incremental cost because the parasitic steam is still fossil), then the voluntary-removal-credit revenue. Each layer is shown explicitly so the reader can trace exactly how the

result is derived. The MAC is reported on a lifetime-tonne basis — NPV of all costs and revenues over the 20-year project life at a 15% discount rate, divided by total atmospheric tonnes abated.

Figure 7 • BECCS layered MAC build-up — recovery + biomass boilers

Plain MAC \$151/t falls to \$103 with the 50% CCUS ITC, rises to \$111 on parasitic NG, reaches break-even at a \$275/t VCM offtake.



Source: Climate Decode mill model. 40 ktCO₂/yr capture; 20-year life; 15% discount rate.

Figure 7. BECCS layered MAC build-up — lifetime-tonne basis (20y @ 15%). Plain MAC of CAD \$151/tCO₂ falls to CAD \$103 with the 50% CCUS ITC, climbs to CAD \$111 once OBPS cost on parasitic NG is added, then drops to roughly break-even with a VCM removal credit at \$275/tCO₂. The project clears the hurdle rate with no margin to spare — VCM offtake price determines the upside.

TABLE 15

Case Study #1 — Layered MAC build-up for BECCS.

Step	Calculation	NPV (CAD M)	Cumulative MAC (CAD/tCO ₂)
1. CAPEX (gross, no incentive)	40,000 × \$1,500 = \$60M (year-0 outlay)	\$60.0	—
2. + PV of OPEX, parasitic elec, parasitic NG	(\$3.6M + \$1.12M + \$0.70M)/yr × PVAF 6.259	\$33.9	—
Sub-total — plain NPV cost	Net abatement 31,138 tCO ₂ /yr; 622,760 lifetime tonnes	\$93.9	+ \$151
+ 50% CCUS ITC (net CAPEX to \$30M)	Reduces NPV cost to \$63.9M	-\$30.0	+ \$103
+ OBPS cost on parasitic NG	7,042 × \$110/yr × PVAF	+\$4.82	+ \$111
+ VCM removal credit	40,000 × \$275/yr × PVAF	-\$68.85	~ \$0

5.6.3 Sensitivity and break-even analysis

The crucial design choice for a BECCS project at a single mill is the voluntary-removal-credit offtake price. With the 50% CCUS ITC, BECCS breaks even at a VCM price of approximately CAD \$275/tCO₂eq on a lifetime-tonne basis (the MAC after ITC + OBPS, before VCM revenue is netted, is CAD \$111/t — exactly recovered by a \$275/t offtake over 20 years at a 15% discount rate). At lower VCM prices, the project loses money; at higher prices, it generates a positive margin that scales linearly with the credit price. Capture is only the first half of the project: BECCS is feasible only where the mill has access either to a suitable geological storage site (a saline aquifer or depleted hydrocarbon reservoir) or to a creditworthy industrial

off-taker willing to take delivery of the CO₂. Mills without nearby access to either route face transport-and-storage costs that can exceed the capture cost itself.

TABLE 16

Case Study #1 — Sensitivity to voluntary removal-credit offtake price.

VCM price (CAD/tCO ₂)	Net MAC (CAD/tCO ₂)	Operating margin (CAD M/yr)	Outcome
\$200	+\$30	-\$18.8	Below break-even
\$250	+\$10	-\$6.3	Slightly below break-even
\$275 (current market median)	~ \$0	0	At break-even
\$300	-\$10	+\$6.3	Marginally positive
\$400 (premium offtake)	-\$51	+\$31.3	Strongly positive

A separate sensitivity is the OBPS price. Because biogenic captures do not earn OBPS credit, raising the federal carbon price does not improve BECCS economics — it actually makes them slightly worse, by raising the OBPS cost on the parasitic NG steam. At the legislated 2030 OBPS ceiling of CAD \$170/t, the parasitic-NG penalty rises to CAD \$12/t (vs \$8 at 2026 prices), pushing the post-ITC MAC from \$111 to \$115. BECCS is structurally a removal-credit and tax-credit lever, not a carbon-price lever. Without VCM offtake, no level of OBPS clears the project.

5.6.4 What the numbers mean

The economic story for BECCS in Canadian pulp & paper is that the project clears only when three layers are present simultaneously: (1) the 50% CCUS ITC, accessed by committing construction before the 2030 step-down; (2) a long-dated voluntary-removal-credit offtake at CAD \$275–\$400/tCO₂, structured as a 10–15-year contract with a creditworthy corporate buyer; and (3) a unified flue-gas configuration in which the NG package boiler, biomass boiler and recovery boiler all vent through the same capture train. Layer (3) keeps the parasitic-NG combustion inside the compliance boundary — its CO₂ is sequestered rather than emitted, eliminating OBPS exposure on the regeneration duty — while ensuring the biogenic share of the captured stream remains large enough to monetize at removal-credit prices. Strip away any one of these three layers and the project does not get built.

5.7 Cost-of-Carbon Case Study #2 — On-Site Biogas Production at the Mill

This case study quantifies the MAC for an on-site anaerobic digestion plant at the same hypothetical 200,000 ADt/yr integrated kraft mill. The plant treats mill primary plus biological sludge (5,000 t-VS/yr) and produces approximately 45,800 GJ/yr of biogas at 60% CH₄ content. After upgrading and combustion-efficiency losses (95% combined), 43,500 GJ/yr of useful energy is delivered, displacing fossil natural gas in the mill's NG package boiler. CFR Gaseous Class credits are computed using the Section 95 credit formula at the current CAD \$250 credit price.

5.7.1 Inputs and key assumptions

TABLE 17

Case Study #2 — On-site biogas. Key inputs and assumptions. No federal/provincial capital grant is applied — the NRCan Clean Fuels Fund closed to new applications in 2024 and CCUS ITC does not extend to biogas combustion.

Parameter	Value	Unit	Source / note
Sludge VS throughput	5,000	t-VS/yr	Default for 200 kADt kraft mill
CH ₄ yield from sludge VS	0.25	m ³ CH ₄ / kg VS	IEA Biogas 2020 mid-range

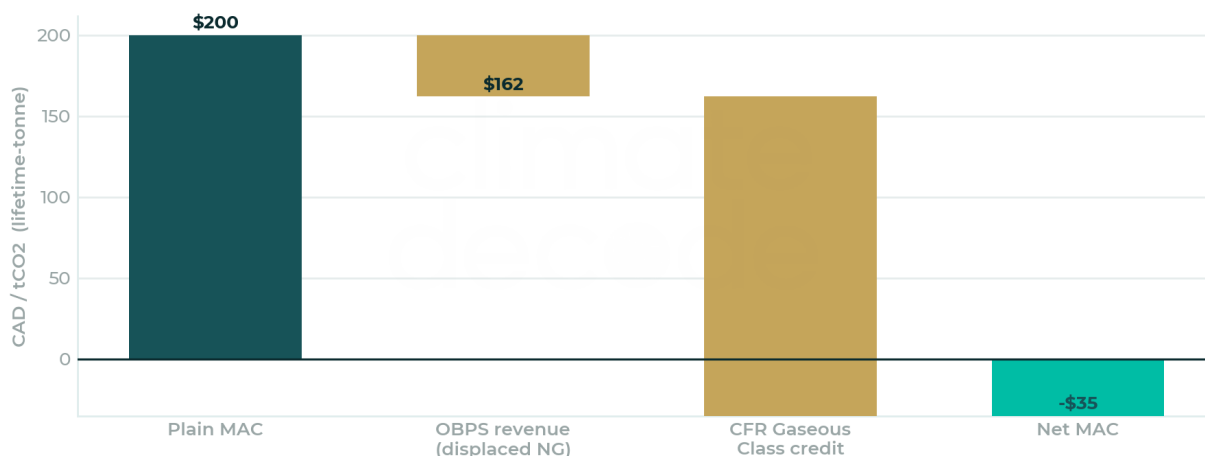
Parameter	Value	Unit	Source / note
Biogas production	45,833	GJ/yr	Computed from yield × LHV
Biogas LHV at 60% CH ₄	22	MJ/m ³	IEA Biogas 2020
Upgrade + combustion efficiency	0.95	—	Vendor-typical PSA upgrading + combustion
Parasitic electricity	30	kWh/GJ biogas	AD blowers + upgrading
Unit CAPEX	150	CAD/GJ-yr biogas	IEA Biogas 2020 + Deloitte W2E RNG 2024
OPEX	4	% of CAPEX/yr	On-site mill ww feedstock is free
CFR Gaseous Class credit price	250	CAD/tCO ₂ e	Conservative mid-market 2026 (range ~\$200–\$400)
CFR per GJ at CI = –32 g/MJ	27.75	CAD/GJ biogas	0.111 tCO ₂ e/GJ × \$250 (Section 95)
Federal OBPS price (2026)	110	CAD/tCO ₂	Canadian federal schedule
Project life / discount rate	20 / 15	years / %	AD plant life; industrial hurdle

5.7.2 Layered MAC build-up

We follow the same layered approach: plain MAC on unsubsidized CAPEX (with operating costs and avoided-fuel savings rolled into the project's lifetime NPV), then OBPS revenue from displaced fossil NG, then the CFR Gaseous Class credit. CFR is added last because it is the largest revenue layer — and is the structural enabler that makes biogas economic. The MAC is reported on a lifetime-tonne basis (NPV / total atmospheric tonnes over the 20-year project life, 15% discount rate).

Figure 8 • On-site biogas layered MAC build-up

Plain MAC \$200/t drops to \$162 once OBPS revenue is netted, then to -\$35/t with the CFR Gaseous Class credit.



Source: Climate Decode mill model. Unsubsidized CAPEX; CFR @ \$250/tCO₂e, CI = -32 g/MJ; 20y @ 15%.

Figure 8. On-site biogas layered MAC build-up — lifetime-tonne basis (20y @ 15%; unsubsidized CAPEX). Plain MAC of CAD \$200/tCO₂ drops to CAD \$162 once OBPS revenue from displaced fossil NG is netted, and to CAD -\$35 once the CFR Gaseous Class credit at \$250/tCO₂e (~\$27.8/GJ at CI = -32 g/MJ) is layered. CFR is the dominant revenue line and the structural project enabler.

TABLE 18

Case Study #2 — Layered MAC build-up for on-site biogas.

Step	Calculation	NPV (CAD M)	Cumulative MAC (CAD/tCO ₂)
1. CAPEX (gross, no incentive)	45,833 GJ-yr × \$150/GJ-yr ~ \$7M (year-0 outlay)	\$7.00	—
2. + PV of OPEX (4% of CAPEX/yr)	\$0.28M × PVAF 6.259	\$1.75	—
3. + PV of parasitic electricity	\$0.11M × PVAF 6.259	\$0.69	—
4. - PV of avoided fossil-NG cost	\$0.22M × PVAF 6.259	-\$1.38	—
Sub-total — plain NPV cost	Net abatement 2,011 tCO ₂ /yr; 40,220 lifetime tonnes	\$8.06	+ \$200
+ OBPS revenue (displaced NG)	2,194 × \$110/yr × PVAF	-\$1.51	+ \$162
+ CFR Gaseous Class	45,833 × \$27.8/GJ × PVAF	-\$7.96	- \$35

5.7.3 Sensitivity — CI as the master variable

Every gigajoule of biogas produced and combusted in the mill displaces a gigajoule of natural gas, doing three things at once. First, it removes the Scope-1 fossil CO₂ associated with the displaced NG, eliminating the OBPS charge on those 2,011 tCO₂/yr — worth roughly CAD \$241,000/yr at the 2026 OBPS price. Second, it cuts the natural-gas fuel bill itself by 45,833 GJ × ~\$5/GJ ~ CAD \$220,000/yr. Third, because the substituted fuel is a Gaseous-Class low-CI fuel under the CFR, the same gigajoules generate CFR credits — roughly CAD \$1.27M/yr at \$250/tCO₂e (CI = -32 g/MJ). The project-level read: a CAD ~\$7M unsubsidised capital outlay produces roughly CAD \$1.0M of net annual operating profit, giving a simple payback of about 7 years and an IRR in the mid-teens — solid on fundamentals even at this more

conservative credit-price assumption. CI is the master variable because it determines both how many CFR credits a given gigajoule generates and how much fossil natural gas a given gigajoule actually displaces.

TABLE 19A

Sensitivity to verified biogas CI (CFR credit price CAD \$360/tCO₂e, OBPS \$110/tCO₂; reference CI = 79 gCO₂e/MJ).

Pathway / feedstock	CI (g/MJ)	CFR (\$/GJ)	Net MAC (\$/tCO ₂)	Outcome
CFR default (no facility data)	61.0	\$4.50	+\$131	Below break-even
Sludge-only, facility-verified	22.0	\$14.25	+\$61	Below break-even
Sludge + food-waste co-digestion	-15.0	\$23.50	-\$5	Near break-even
Manure + food-waste (case midpoint)	-32.0	\$27.75	-\$35	Mildly positive
Manure-rich (methane-destruction credit)	-150.0	\$57.25	-\$245	Strongly positive

TABLE 19B

Net MAC sensitivity to CFR credit price × OBPS price (holding CI = -32 g/MJ, case midpoint).

CFR price (~ \$/GJ)	OBPS \$50/t	OBPS \$110/t (2026)	OBPS \$170/t (2030)
\$200/tCO ₂ e (~ \$22/GJ)	+\$25	+\$5	-\$16
\$250/tCO ₂ e (~ \$28/GJ)	-\$15	-\$35	-\$55
\$300/tCO ₂ e (~ \$33/GJ)	-\$54	-\$75	-\$95
\$360/tCO ₂ e (~ \$40/GJ)	-\$102	-\$122	-\$143
\$500/tCO ₂ e (~ \$56/GJ)	-\$212	-\$233	-\$253

The two policy levers are not equally weighted. OBPS moves the Net MAC by roughly ±\$20/tCO₂ across its full legislated range (\$50 to \$170/t) on a lifetime basis — meaningful but not decisive. CFR moves the Net MAC by roughly \$250/tCO₂ across its plausible 2026 market range (\$200 to \$500/tCO₂e), and at any CFR price above ~\$220/tCO₂e the project clears at the 2026 OBPS rate regardless. Without CFR, the break-even OBPS price would be approximately \$580/tCO₂ — well above the legislated 2030 federal ceiling of \$170/t. Fuel-side credits and compliance-price instruments are complements, not substitutes — CFR rewards the gigajoule of low-CI fuel produced, OBPS rewards the tonne of fossil CO₂ avoided, and the project needs both signals firing in the same direction to clear at scale.

5.7.4 What the numbers mean

On-site biogas at the small-to-medium kraft mill scale is economic without capital subsidy when two conditions are met: a registered CFR Gaseous Class pathway with an optimized lifecycle CI, ideally leveraging avoided-methane LCA credit from the displaced wastewater-treatment baseline; and long-term CFR-credit offtake to insulate against credit-price volatility. The 2025 federal election made the policy risk visible in stark terms: the official opposition campaigned on repealing the Clean Fuel Regulations, and although CFR survived, the eighteen-month period during which its forward existence was a partisan-political question imposed a real risk discount on every CFR-dependent project in development. A 25-year industrial asset cannot be underwritten against a revenue stream an investment committee believes could be legislated away in a single Order-in-Council. The structural fix is durable, multi-Parliament policy certainty on the CFR architecture itself. A second gap is on the capital side: unlike BECCS (50% CCUS ITC) and low-carbon hydrogen (Clean Hydrogen ITC at 15–40%), on-site

biogas at mill scale has no comparable federal capital-cost incentive — the NRCan Clean Fuels Fund closed to new applications in 2024. The policy gap to close is a federal Clean Fuel Production ITC, directly analogous to the U.S. §45Z producer credit on a per-GJ basis.

5.8 Strategic Implication — High Upfront Cost and the Role of Policy Certainty

Both case studies expose the same structural feature: project economics depend on a layered revenue stack composed of carbon-market signals, tax credits, fuel-side credits, and voluntary-market offtakes. None of these levers operates in isolation, and none of them can be evaluated without long-term visibility into the others. But the two cases break down differently when that visibility is removed, and the policy reforms each one points to are also different.

The real bottleneck

In every project we model, the bottleneck to greenlighting is rarely the technology or the carbon-price level. It is the multi-year visibility of the revenue layers — the OBPS schedule, the ITC schedule, the CFR market structure, the voluntary-removal-credit offtake counterparty. Without that visibility, even MAC-negative projects sit on the shelf.

Read together, the BECCS and biogas cases expose three structural fragilities that affect industrial decarbonization broadly, not just pulp & paper. None of them is about technology readiness, abatement cost, or the level of the carbon price. All three are about how the policy stack performs over time.

Revenue layering creates compound policy exposure. Neither case clears on a single instrument. Both projects assemble their economics from four to six independent revenue layers — compliance carbon pricing, capital tax credits, fuel-side credits, voluntary offtake contracts, fuel-cost savings, sometimes provincial top-ups — each of which is a separate failure mode. A capital-allocation committee underwriting a 25-year asset is implicitly underwriting all of those instruments simultaneously, and any one of them weakening over the asset life can flip the project from MAC-negative to MAC-positive. The more layers a project depends on, the more exposed it is.

Policy reversibility kills long-dated assets faster than policy stringency does. What a project needs from a policy regime is not maximum generosity — it is multi-decade readability. The 2025 federal election made this visible: a regulation that had been operating well saw its forward existence become a partisan-political question for eighteen months, and every project that depended on it was repriced for that risk during the campaign window. The same dynamic applies to ITC construction-start windows that step down on legislated dates, to voluntary-credit frameworks that depend on standards bodies revising methodologies, and to compliance-credit prices that depend on benchmark trajectories holding through future governments. A committee can underwrite a modest revenue stream that is durable for 20 years; it cannot underwrite a generous one that may not exist in five.

Capital-side and revenue-side incentives are not interchangeable. High upfront cost and long-dated revenue uncertainty are different problems requiring different instruments. Capital-side instruments — ITCs, refundable credits, grants — de-risk the year-zero outlay and let projects clear the financing gate. Revenue-side instruments — compliance carbon prices, fuel-side credits, voluntary offtakes — sustain operating margin across the asset life. Today's federal stack supports some Scope-1 fossil-displacement levers (CCUS, low-carbon hydrogen) on both sides, but supports others (on-site biogas, certain electrification pathways) on the revenue side only. That asymmetry distorts deployment sequencing — capital flows toward better-supported technologies even when the lesser-supported ones have stronger operating economics.

SECTION 06

How Climate Decode TerraNova Helps

06

TerraNova is an agentic-AI decarbonization manager for industrial emitters. It is the tool that turns the analytical workflow described in this paper — operations data, hotspots, levers, policy stack, financing — into a single decision-ready output for a specific mill. TerraNova drives a fully-populated mill model that captures actual energy and production data, allocates emissions to each process step, screens more than fifty decarbonization levers against the local policy and carbon-market environment, and returns a finance-grade investment plan: ranked portfolio, sequenced deployment schedule, NPV / IRR / payback at lever and portfolio level, year-by-year compliance position, and the revenue stack that supports each project. The underlying calculation engine is an Excel-based model that lives behind the agent; the point of TerraNova is to lift decarbonization from a months-long bespoke consulting exercise into a quarterly-refreshable, board-ready output.

6.1 What TerraNova does

- Ingests mill data — fuel, electricity, and production at the frequency the company actually reports (monthly, quarterly, or annual) — and produces a complete Scope-1, Scope-2, and biogenic emissions inventory aligned with the GHG Protocol and the relevant regulatory boundary (federal OBPS, EU and UK ETS, U.S. GHGRP).
- Allocates mill totals across the process steps that drive them, surfacing the steam-, electricity-, and direct-emission hotspots in the form developed in §3.4.
- Screens a catalog of more than fifty decarbonization levers against the mill's actual energy mix and the local policy stack — carbon price, OBPS benchmark, CFR Gaseous Class credits, CCUS ITC, §45Q, §45V, Clean Hydrogen ITC, provincial top-ups — and characterises each lever along ten dimensions including annual abatement, CAPEX, OPEX, grant capture, TRL, and MAC computed both with and without the OBPS revenue layer.
- Builds a portfolio: lets the user select pathway type (SBTi-aligned, federal OBPS annual benchmark, or custom), set CAPEX budget caps, and toggle individual levers. Returns a sequenced deployment schedule, an emissions-trajectory chart, and a MACC waterfall ranked by ascending cost.
- Runs the financials: a 10-year discounted cash flow with the carbon-price trajectory, energy-price forecast, abatement ramp, ITC and grant capture, OBPS revenue, CFR credit revenue, and voluntary removal-credit revenue, plus a full cash-flow statement. Outputs NPV, IRR, modified IRR, discounted payback, and benefit-cost ratio at both the lever and portfolio level.
- Tracks compliance year-by-year against the applicable regime's tightening benchmarks, so the company can see exactly when the selected portfolio moves it from deficit to surplus position and how the surplus credit balance evolves.

What it replaces

TerraNova integrates four workflows that have historically lived in different teams and tools — GHG inventory, marginal-abatement cost analysis, project-level financial modelling, and compliance-position tracking — into one coherent decision system. The mill operator does not have to commission a separate study for each, reconcile inputs across consulting reports, or rebuild the analysis when policy changes or fresh utility data come in. The strategy can be revisited every quarter against the latest carbon prices, tax-credit parameters, and energy-price forecast, and the underlying model stays consistent across iterations — which is what makes the output finance-grade rather than indicative.

SECTION 07

Conclusions and Recommendations

07

The pulp & paper sector occupies a privileged position in industrial decarbonization. Its biogenic-heavy fuel mix means a relatively small fossil-emissions footprint (~2% of industrial CO₂) despite high energy intensity. That same biogenic flux — over 500 Mt CO₂/yr — is the world's most accessible feedstock for engineered negative emissions through BECCS, potentially turning the sector from small emitter to major CO₂ sink in the second half of this century. Capturing that opportunity requires the operational discipline to align mill-level data, lever selection, policy access, and financing capacity into a single sequenced plan.

FOR THE BOARD

Key takeaways

- Deploy energy-efficiency measures with negative MAC under any policy scenario — heat recovery from bleach effluent, shoe press, VFDs — without waiting for carbon-price clarity.
- Build the analytical infrastructure (data flow from operations to emissions to MACC to financials) before committing capital. Quarterly-updateable models structurally outperform one-off consultant MACCs.
- Engage with VCM offtake counterparties early. BECCS economics are extremely sensitive to long-term removal-credit prices; pre-committed offtake at \$250+/tCO₂ is now achievable for high-integrity projects.
- Capture the §45Q and Canadian CCUS ITC window — construction must begin pre-2033 (U.S.) or pre-2030 (Canadian full rate) to access maximum incentive value.
- Stack CFR Gaseous Class credits with avoided NG cost and compliance carbon for any on-site biogas project — the dual-monetization is unique in North American policy.
- Use a live model to evaluate every lever decision in the context of the full revenue stack — not just tech-only MAC.

ANNEXURE A

The Sector-Wide Pathway — IEA Scenarios to 2050

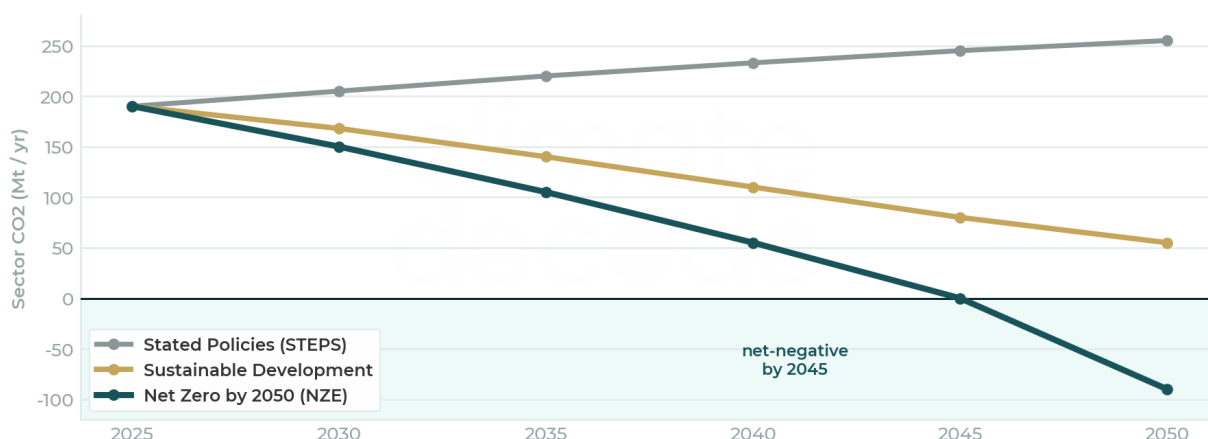
A

The mill-level economic logic established in the body of this paper plays out at the sector level along trajectories the International Energy Agency (IEA) traces in its periodic World Energy Outlook and Net Zero Roadmap publications. IEA modeling places pulp & paper on three contrasting paths between today and 2050: a Stated Policies Scenario (STEPS) tracking continued growth in production with limited new abatement; a Sustainable Development Scenario (SDS) consistent with Paris-aligned 2 °C trajectories; and a Net Zero Emissions by 2050 (NZE) scenario consistent with limiting warming to 1.5 °C. Each implies a different role for the sector.

A.1 Sector Emissions Trajectory — Three Scenarios

Figure A.1 • Pulp & paper sector CO₂ trajectories to 2050

Net Zero turns the sector net-negative by 2045 via large-scale BECCS on recovery and biomass boilers.



Source: IEA scenario framing (STEPS / SDS / NZE). Values indicative of stated endpoints.

Figure A.1. P&P sector CO₂ emissions trajectories under IEA Stated Policies, Sustainable Development, and Net Zero by 2050 scenarios. NZE turns the sector net-negative by 2045 via BECCS deployment.

Under Stated Policies, sector emissions continue to grow with global paper output — reaching ~255 Mt CO₂/yr by 2050. The Sustainable Development Scenario halves emissions to ~55 Mt CO₂/yr through aggressive efficiency, fuel switching, and incremental capture. The Net Zero scenario goes further still: by 2045 the sector becomes net-negative, sequestering CO₂ on net through large-scale BECCS deployment on recovery and biomass boilers. The gap between current trajectory and NZE in 2050 is approximately 345 Mt CO₂/yr — a measure of the abatement, electrification, and removal that must be deployed sector-wide over the next 25 years.

A.2 Energy Mix Transformation Under Net Zero

Figure A.2 • Global P&P energy mix under IEA Net Zero

Fossil falls 92%; electricity more than doubles; RNG and low-carbon hydrogen scale from zero to ~5 EJ.

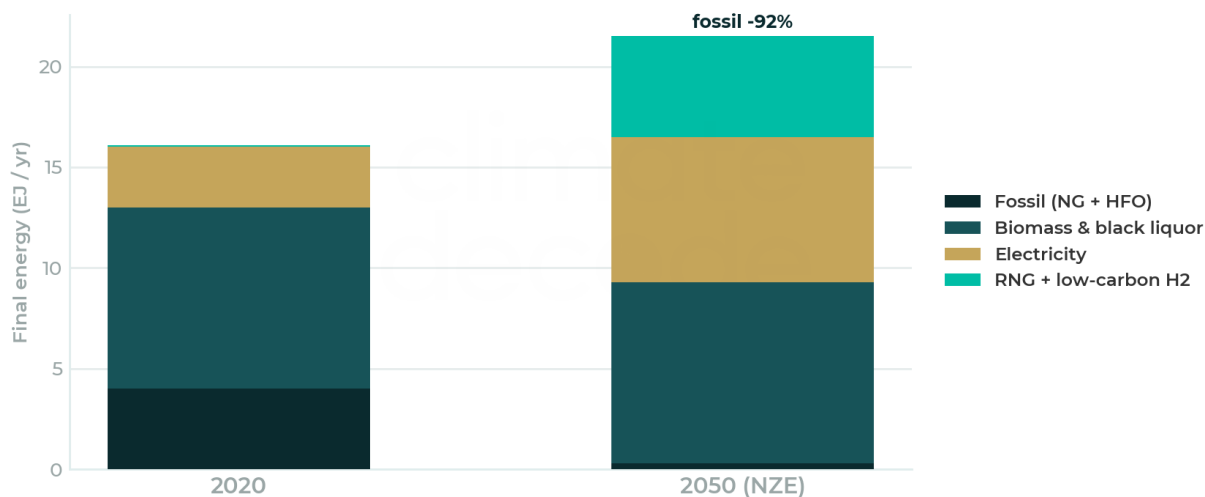


Figure A.2. Global P&P energy mix transformation under IEA Net Zero by 2050. Fossil falls 92%; electricity more than doubles; RNG and low-carbon hydrogen scale from zero to ~5 EJ combined.

The IEA Net Zero scenario sees fossil natural gas plus heavy fuel oil decline from ~4 EJ/yr in 2020 to ~0.3 EJ/yr by 2050 — a 92% reduction in absolute terms. Biomass and black liquor remain the largest single category but their role shifts: combustion CO₂ is increasingly captured (BECCS), making the same fuel a vehicle for negative emissions rather than a neutral status-quo. Electricity rises from 3 EJ to 7+ EJ as heat pumps, MVR, and electric boilers replace direct fossil heat. RNG and biomethane plus low-carbon hydrogen — both at trace levels in 2020 — together supply ~5 EJ by 2050 in lime kilns and high-temperature heat applications. At the mill level this requires electrification of heat (25–40% of fossil-NG steam by 2035), BECCS at scale (60–80% sector-wide capture by 2045), RNG production and procurement, low-carbon hydrogen in lime-kiln burners, and the always-on demand-side efficiency that reduces required BECCS, RNG, and hydrogen supply downstream.

A.3 Investment Implication — The Capital Mobilization Challenge

IEA estimates that meeting the Net Zero pathway in P&P globally requires roughly \$80–120 billion of incremental decarbonization CAPEX between 2025 and 2050 — concentrated in BECCS retrofits (\$40–60 B), heat pumps and electrification (\$20–30 B), RNG and biogas (\$10–15 B), green hydrogen and electric calcination (\$5–10 B), and energy efficiency (\$5–10 B). The latter is the smallest line item but produces the greatest leverage on every other capital decision. The other lines all deliver superior risk-adjusted IRR when compliance, tax-credit, and voluntary-market revenue is fully captured; the structural challenge is sequencing investments and aligning capital availability with the policy windows (\$45Q construction-start by 2033, Canadian CCUS ITC full rate to 2030).

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