



Advanced nuclear reactor integration opportunities for the pulp and paper industry in the U.S. context: Technical perspectives, gap analysis, and preliminary technoeconomic assessment

Changing the World's Energy Future

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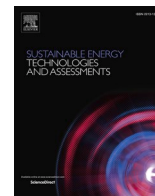
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Advanced nuclear reactor integration opportunities for the pulp and paper industry in the U.S. context: Technical perspectives, gap analysis, and preliminary techno-economic assessment

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ABSTRACT

Pulp and paper (P&P) manufacturing requires a large amount of low-pressure (LP) steam to digest, wash wood fibers and dry pulp into paper. Most of the LP steam is extracted from backpressure turbines that produce power from high-pressure (HP) steam. This HP steam is generated from burning wood waste material; bark is burned in hog boilers, and lignin is boiled in a black liquor recovery boiler. In a typical integrated P&P mill, 50–100% of the steam is produced from these sources, while additional steam is produced in natural gas (NG), fuel oil, or coal boilers. The other energy-intensive process in the plant is the chemical-recovery section (e.g., lime kiln), which requires high-temperature processing from NG combustion to retrieve and recirculate spent chemicals. This paper assesses the energy and heat demand and material balances of a typical generic kraft pulp mill, along with the nuclear heat, steam, and power integration opportunities to replace conventional combustion systems. The paper also addresses steam and electricity generation through a comprehensive technical and engineering gap analysis of five different nuclear-integration opportunities and their process economics, thus enabling the lignin and bark to be further processed into biobased chemicals or fuels, as well as the potential to reduce overall emissions from kraft pulping. Preliminary findings have shown that the P&P industry could achieve technological benefits by integrating their current manufacturing process with small modular nuclear reactors (SMNRs) on a national level. This research aims to set the path forward for a cleaner and more resilient P&P industry.

Introduction

Kraft pulping constitutes 80 % of the total chemical pulping industry, making it the predominant method employed worldwide [1]. Wood chips are digested in white liquor at elevated temperature and pressure. After digestion, the leftover contents are washed to separate the pulp from the spent-cooking liquid, defibrated, washed and bleached [2]. The main advantage of the kraft process is the recovery and recycling of spent chemicals, where these are later regenerated and the strong (concentrated) black liquor is fired in a black liquor recovery boiler (BLRB), to provide heat for the pulping process [3]. A simplified diagram of the kraft pulping process is provided in the [supplementary materials](#).

In 1994, recovery boilers represented 35 % of total boiler capacity in the United States (U.S.) pulp and paper (P&P) industry. Including other waste fuels, about 50 % of boiler capacity is fueled by the chemical-

recovery process and its byproducts [4]. The recovery boiler provides up to 100 % of the total energy requirement for market pulp mills, where the percentage for integrated mills widely varies based on the P&P production capacities. The remaining energy requirements are met by conventional fossil fuels, such as NG, fuel oil, or wood boilers. The wood-boiler fuel commonly consists of solid-wood waste produced at the mill. Additionally, the lime kiln is typically fired with NG or fuel oil because of its sensitivity to high-temperature levels and contaminants [5,6].

Despite innovations, carbon dioxide (CO₂) is emitted from the burning of lignin in the recovery boiler, the combustion of wood waste, the calcination of lime, and the usage of fossil fuels [7,8]. About 80 % of CO₂ emissions stem from biogenic sources, while 20 % comes from NG or other alternative fossil fuels [7,8], a detailed table for typical fuel sources in the P&P industry and its associated emissions in MMT CO₂-eq

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is provided in the [supplementary materials](#).

In addition to tracked greenhouse gas (GHG) emissions, other air emissions from paper mills represent health and environmental risks. The recovery furnace, lime kiln (calcination), and smelt dissolving tank (recausticizing) primarily contribute to the total emissions resulting from the carryover of solid particulates and the sublimation or condensation of inorganic chemicals. The distinct odor associated with pulp mills is attributed to chemical emissions—especially reduced sulfur compounds, such as hydrogen sulfide, methyl mercaptan, dimethyl sulfide, and dimethyl disulfide [9–12]. These compounds, emitted from various mill points, can cause serious adverse health effects due to their low-odor thresholds. The direct-contact evaporator is a major source of hydrogen sulfide emissions. Reactions with lignin contribute to methyl mercaptan and dimethyl sulfide formation arising from digesters and blow tanks [9–12]. A detailed table of measured air pollutant emissions generated by P&P mills, along with their associated emissions, is available in the [supplementary materials](#).

Reliance on fossil fuels for energy-intensive processes such as pulp digestion, drying, and bleaching contributes significantly to the industry's GHG emissions. As current initiatives for energy independence demand the use of reliable energy sources along with significant reductions in GHG emissions, alternative energy sources have gained prominence. Among these, nuclear energy emerges as a transformative solution for the P&P industry. Unlike fossil fuels, nuclear energy provides a consistent and high-density energy supply with near-zero GHG emissions, aligning with environmental, technological, and economic goals toward advanced energy deployment. By integrating nuclear power into the industry's energy portfolio, companies can achieve substantial operational benefits, including cost stability, enhanced process efficiency, and alignment with innovative next-generation integrated systems. SMNRs are a suitable option for integration with P&P mills because they can provide both heat and steam, they have a compact footprint and a small emergency-planning zone that allows them to be located close to the point of use, and they have a long operational lifespan that aligns with the expected lifetime of the mills.

In addition, this integration can address fluctuating energy costs and supply chain vulnerabilities that hinder competitiveness. Furthermore, advanced nuclear technologies, such as SMNRs, are particularly well-suited for industrial applications due to their scalability, safety, and compatibility with cogeneration systems. These reactors can provide the thermal and electrical energy required for P&P production, enabling a seamless transition to a local and affordable energy source. This paper explores the technical, economic, and environmental implications of incorporating nuclear energy into the P&P industry, highlighting its potential to revamp processes while meeting industry goals and thermal demands. Through a comprehensive analysis of five different nuclear-integration opportunities, this research aims to set the path forward for a cleaner and more resilient industry.

Research methodology

Determination of the U.S. P&P kraft mill production capacities: nationwide distribution and locations

The total number of kraft mill pulping facilities in the U.S and their state-by-state capacities were determined by gathering the data acquired from the FisherSolve Database [13]. As of the second quarter of 2023, 105 operating P&P facilities were identified across the country, 85 of which are kraft pulp mills. 69 of these mills are clustered in the southeastern region, due to the abundant biomass feedstock availability and logistical advantages for transportation and distribution in this area. Alabama, Georgia, Mississippi, North Carolina, Louisiana, South Carolina, and Florida are the major wood pulp producers in the U.S., as indicated in [Table 1](#).

Determination of the U.S generic reference kraft pulp mill capacity

As generally occurs with all diverse production sectors, the kraft pulping capacities for each mill located across the U.S. could vary over years or months due to upgrades, complete shutdowns, expansions, or ownership changes. This variability is affected by feedstock quality (heterogeneity) and the challenges associated with woody biomass processing. For reference purposes and determining energy requirements, the yearly average and median capacities for the total number (85) of kraft mills in the U.S. were calculated at about 650,000 and 623,000 air-dried-tonnes/year (ADt/yr), respectively [14]. A reference plant was established with a capacity of 400,000 ADt/yr, accounting for ~ 35 % of the total number of kraft mills in the U.S. [14]. These parameters and distributions are reflected in [Fig. 1](#). A below-median capacity was chosen as the reference capacity, since about 35 % (i.e., 30) of these kraft pulp mills operate within this annual capacity and use batch digesters, whereas the remaining mills utilize more than four paper machines to increase their annual production, and may use a combination of batch or continuous digesters to process larger quantities of wood chips on a yearly basis.

Determination of the U.S generic reference kraft pulp mill configuration

A study performed by Future Market Insights illustrated the global unbleached softwood kraft pulp market was estimated to be worth about U.S. \$1,481.5 million in 2023 [15]. Projecting that number out further over the next 10 years, this market was expected to expand at a compound annual growth rate of 4.6 %, with a year-on-year growth rate of 3.5 % in 2023. Consequently, this market is anticipated to reach U.S. \$2,322.84 million by 2033 [15]. As such, the future of unbleached softwood kraft pulp in end-use industries, along with the anticipated advancements to come, is promising and expected to remain stable—or even increase—in the future. Therefore, the advanced nuclear reactors integrated with the P&P industry reported in this work are mainly focused on the typical unbleached softwood (southern) kraft pulping

Table 1
U.S. pulp production share by state [13].

State	Count	Capacity	Share	State	Count	Capacity	Share
AL	11	6,362,870	12 %	NY	2	275,125	1 %
AR	5	2,115,645	4 %	OH	1	462,941	1 %
FL	6	2,639,369	5 %	OK	1	1,554,350	3 %
GA	11	7,675,863	14 %	OR	4	1,909,905	4 %
ID	1	731,002	1 %	PA	2	673,642	1 %
KY	2	1,138,225	2 %	SC	6	3,823,140	7 %
LA	7	6,670,045	12 %	TN	2	1,127,835	2 %
ME	5	1,900,948	4 %	TX	3	2,064,820	4 %
MI	3	1,431,090	3 %	VA	6	2,695,280	5 %
MN	2	1,123,385	2 %	WA	6	2,568,179	5 %
MS	4	2,809,600	5 %	WI	5	499,757	1 %
NC	5	1,979,859	4 %	Total	100	54,232,875	100 %

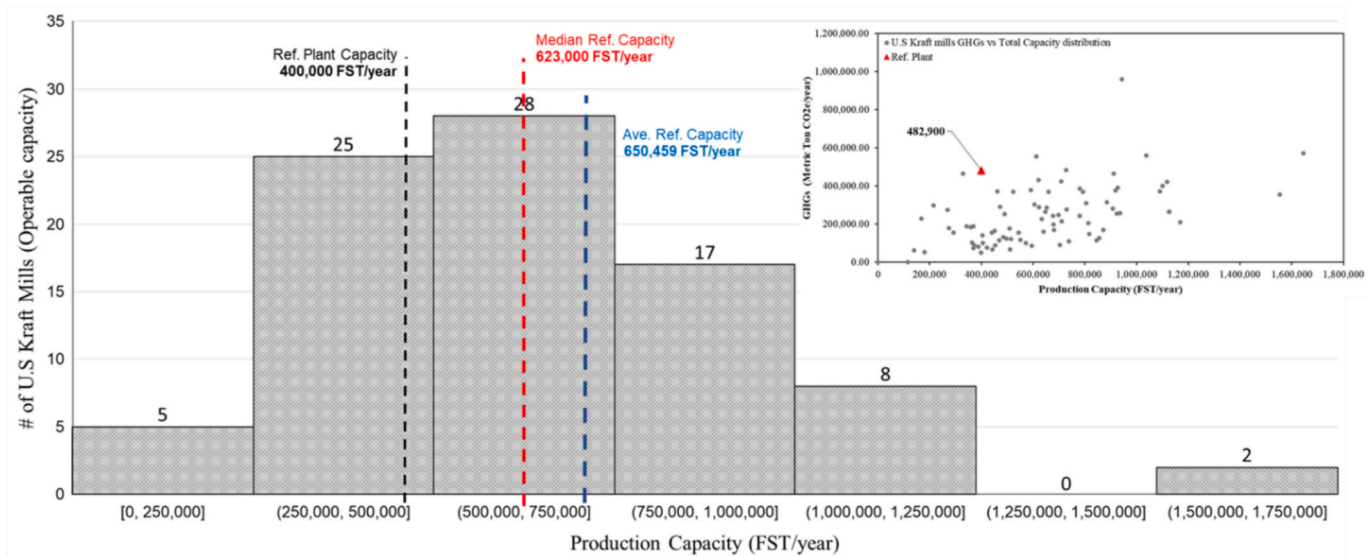


Fig. 1. Nationwide kraft pulp mill capacity distribution chart and correlation of GHG emissions vs Production capacity.

process, as observed in Fig. 2. Within the industry, there is no such thing as a “typical” P&P mill, as each mill tends to vary in terms of technology type and capacity. For example, some integrated mills produce a large portion of market pulp but include small papermaking operations. Others may use a large quantity of recycled materials and only a fraction of virgin pulp. However, the process mechanisms and layouts of all kraft integrated mills are similar and well-documented, thus enabling the energy demands and mass balances to be estimated from these reference values.

operating kraft mills in the U.S. was conducted by gathering all the plant capacity data and their corresponding GHG emissions (CO₂-eq.) [13,16]. The total emissions generated from biogenic + non-biogenic sources were seen to roughly correlate with the plant capacities, though the coefficient of determination (r²) suggests a small correlation of MMT CO₂-eq./year. However, a positive relationship is observed between the number of finished tons of dry pulp and the emissions generated by the plant, as observed in Fig. 1 inset. This variability can be attributed to the variety of kraft pulping equipment and machinery, the age and energy efficiency of the mills, and the technologies involved.

CO₂ emissions estimations for kraft pulping on a national scale

An initial correlation for the total CO₂ emissions produced by all

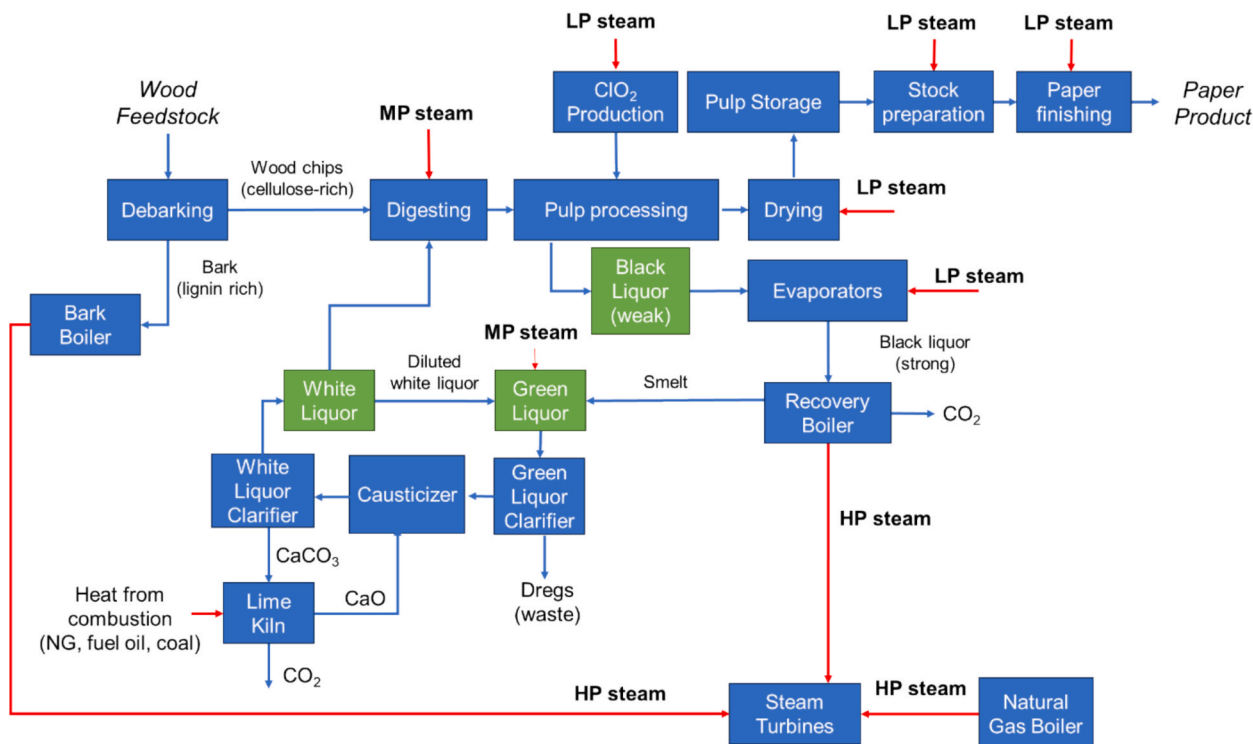


Fig. 2. Block flow diagram of a typical southern kraft pulping process.

Reference process details

An annual capacity of 400,000 ADt was assumed for the reference kraft P&P mill, for a final pulping yield of 46 wt% (wt.%), which falls within the range of industrial operation yields (40–55 %) [17]. An Excel spreadsheet provided by an industry partner in the P&P industry, which was based on real operational conditions, chemical dosages, and other process parameters, was used to estimate the mass and energy balances, process-energy demands, and CO₂ emissions for the reference pulping process.

Table 2 summarizes the streams and total flow rates of the process, while the corresponding process flow diagram for the reference kraft mill is provided in the [supplementary materials](#).

The reference kraft mill's energy and steam demands are taken from the Excel spreadsheet-based model, which provides the power and heating duty demands of the high-pressure (HP), medium-pressure (MP), and low-pressure (LP) steam generated at the recovery boiler, the heating duty from black liquor, and from fuel combustion. The energy balance summary can be seen in [Table 3](#).

Technical analysis of nuclear-integration opportunities in the P&P industry

Four types of opportunities exist to replace conventional combustion systems in the P&P industry:

- **Electrical integration** – A simplest pathway to integrate an SMNR with any industrial facility is to simply replace any grid import with nuclear electricity. This approach has limited potential for CO₂ reductions in P&P, as the electrical requirement at the reference mill is low compared to the combustion processes (e.g., BLRB, lime kiln,

hog fuel boiler) being used. Further, the steam generated by these processes, as well as the auxiliary natural gas (NG) boilers is expanded in the Combined Heat and Power (CHP) equipment, cogenerating some or all the required electricity while adjusting the temperature and pressure of the main steam. This option is limited in P&P because most of the U.S mill configurations (including the reference mill) are electricity self-sufficient (or nearly so). Recent studies in Nordic countries have shown that modern energy-efficient mills can produce a surplus of electricity to distribute to their local electricity grid [19], restricting the impact of this opportunity. However, other studies have shown that if certain heating duties at the mill are electrified, the opportunity for integration of nuclear electricity may be increased [20,21].

- **Steam integration** – The SMNR can generate supplemental steam within the existing CHP system to back out the NG consumption, bark/fine combustion in the hog boiler, and lignin combustion in the BLRB if chemical delignification processes are implemented. Steam and electrical demands may be increased if the solvent-based flue gas CO₂-capture technology is implemented to reduce the GHG emissions of the mill.
- **Hydrogen integration** – The SMNR can produce hydrogen through high-temperature steam electrolysis (HTSE). This hydrogen then could be blended into or replace NG in boilers, furnaces, and kilns, providing some of the combustion duty of the mill without the associated GHG emissions.
- **Oxy-fuel combustion** – The oxygen (O₂) byproduct of HTSE can be swept from the electrode with clean CO₂ instead of air, resulting in a stream that is composed almost exclusively of CO₂ and O₂. Using this stream to combust biogenic fuels increases the CO₂ content of the flue gas to a level that greatly reduces the cost of sequestering the CO₂.

Table 2
Pulp mill stream flow rates.

Stream	Components	Total Flow Rate (mt/day)	Stream	Components	Total Flow Rate (mt/day)
1	wood logs	2,554	21	black liquor	2,208
2	bark and fines	230	22	flue gas (CO ₂ emissions)	1,240
3	debarked logs	2,324	23	steam	5,407
4	screening fines	76	24	green liquor	529
5	woodchips	2,248	25	Make-up lime	329
6	turpentine + H ₂ O	8	26	slacked lime	1,103
7	white liquor	3,929	27	white liquor + lime mud (CaCO ₃)	1,216
8	digested woodchips	2,240	28	white liquor	3,929
9	extracted liquor	11,434	29	lime mud	735
10	vapors	2,986	30	lime mud	1,320
11	black liquor	8,448	31	NG, LPG, fuel oil	36
12	soaps and tall oil	104	32	gases, water and dust (CO ₂ emissions)	131
13	black liquor	4,128	33	lime CaO	246
14	vapors	2,882	34	weak wash	662
15	black liquor	4,128	35	digested wood chips	13,423
16	extracted liquor	537	36	unrefined pulp	34,649
17	black liquor	3,591	37	pulp (bdt)	1,029
18	vapors	1,383	38	Make-up black liquor	8,690
19	concentrated black liquor	2,208	39	turpentine and water	8
20	condensate	251			

Economic assessment for nuclear-integration opportunities in the P&P industry

Technoeconomic analysis

Technoeconomic analysis (TEA) is a critical tool for evaluating the feasibility and economic viability of integrating SMNRs into industrial operations. The present method assesses both the technical potential and financial implications of incorporating nuclear energy systems, aiming to provide stakeholders with data-driven insights for informed decision-making. In this study, the TEA explores the integration of an advanced nuclear reactor with a P&P kraft mill, focusing on the capacity of the reactor to supply heat, steam, and power, as well as to mitigate emissions and enhance overall process efficiency.

This study employed two tools developed by the Idaho National Laboratory (INL) to conduct the TEA: (1) the Standardized Economic Tool (SET), and (2) the Nuclear-Integrated Hydrogen Production Analysis (NIHPA) tool. Both tools were used to evaluate the financial and economic viability of integrating SMNRs and HTSE systems into P&P mill operations. This section outlines the economic modeling methods that were employed, including the key assumptions and tools. Detailed information regarding the SET and NIHPA tools can be seen in the [supplementary materials](#).

The analysis employs a multi-scenario approach, considering variations in reactor configurations, integration methods, and financial incentives. The primary model includes a business-as-usual (BAU) scenario, which represents the current state of operations without nuclear integration, serving as a comparative benchmark. Additionally, there are integration scenarios, which incorporate nuclear energy in configurations such as the cogeneration of heat and electricity, HTSE hydrogen production, and alternative synthesis pathways.

By quantifying the financial and environmental impacts, this approach bridges technical feasibility with economic rationality to analyze the adoption of cleaner technologies. The methodology and data calibration are described below.

Table 3
Overall energy requirements for the reference pulp mill.

Pulp Mill Detailed Energy Requirements						
Process Unit	Power Consumption	Heat from Fuel Combustion	Steam Consumption	Steam Quality	Byproduct Fuel Source	Heat of Combustion of Byproducts (LHV)
	MWe	MWth	MWth	–	–	MWth
Wood Processing	1.4	–	–	–	–	–
Hog Fuel Boiler	2.0	–	–	–	bark & fines	23.8
Pulp Plant	8.6	–	29.8	LP, MP	–	–
Bleaching*	0.7	–	22.6	LP, MP	–	–
Pulp Drying*	5.2	–	47.4	LP	–	–
Evaporation Plant	1.4	–	32.5	LP, MP	–	–
Lime Kiln + Causticizing	0.9	28.1	–	–	–	–
Recovery Boiler	3.1	–	24.1	LP, MP, HP	black liquor solids	161.0
Wastewater Plant*	2.0	–	–	–	–	–
CHP system	–26.6	45.0	–156.0	LP, MP, HP	–	–185.0
Total	–1	73	0	–	–	185

* The values for the bleaching, pulp drying, and wastewater plants came from Reference [18].

Discounted cash-flow model

With financial-planning purposes, such as buying or selling companies, making a new investment, or enhancing a business, companies make financial valuations of different assets. For instance, company valuation is the process of assessing the total economic value of a business and its assets, evaluating all aspects to determine the current worth for sale-value and tax-reporting purposes. While a simple method involves subtracting liabilities from assets, more comprehensive approaches include book value, discounted cash-flow analysis, market capitalization, enterprise value, earnings, and the present value of a growing perpetuity formula, thus providing deeper insight into a company's financial standing [22]. This multiplicity of methods creates a challenge given there is no explicit agreement on what approach should be used [23]. To overcome this challenge and provide clear guidelines of what approach should be followed, this paper follows the practices of the Chartered Financial Analyst (CFA) Institute [23] to calculate equity value.

$$EBITDA = Net\ Income + Taxes + Int + Dep$$

$$Net\ Income = Revenue - Fixed\ O\&M - Variable\ O\&M$$

Revenue is the revenue from the sale of the production

Fixed operating and maintenance (O&M) are the cost associated with operating the plant, which varies with the production level

Variable O&M is the cost associated with operating the plant that does not vary with the production level

Int are the interest expenses

Dep is depreciation

CAPEX is the capital expenditure

WCI is the working capital investment.

Similarly, the FCFE is calculated according to Equation (3).

$$FCFE = EBITDA*(1 - TR) + Dep*(TR) - CAPEX - WCI - Int(1 - TR) + Net\ borrowing \quad (3)$$

When valuing companies or investments, it is possible to focus on either free cash-flow to the firm (FCFF), which is the cash-flow available to all investors, or free cash-flow to equity (FCFE), which is the total cash-flow available to common stockholders. However, these cash-flows should not be confused with the sum of returns. It is vital to note that the free cash-flow can be used as the return in cases where the company does not pay dividends, pays dividends that differ significantly from its capacity to pay, shows free cash-flow that aligns with profitability within a reasonable forecast period, or when the investor adopts a control perspective [23].

Following the 2024 CFA guidelines, the firm value can be calculated according to Eq. (1).

$$Firm\ Value = \sum_{t=1}^{\infty} \frac{FCFF_t}{(1 + WACC)^t} \quad (1)$$

Estimating the present value of the FCFF or the FCFE requires obtaining the value of the firm or the investment to the shareholders and discounting it by the corresponding discount rate. Following the 2024 CFA guidelines, the FCFF can be calculated using Equation (2).

$$FCFF = EBITDA*(1 - TR) + Dep*(TR) - CAPEX - WCI \quad (2)$$

where,

Re-arranging results in Equation (4).

$$FCFE = FCFF - Int*(1 - TR) + Net\ Borrowing \quad (4)$$

where,

Net borrowing is the total debt borrowed during the year minus the amount of debt repaid during the year.

WCI is defined as the net of the current assets and the current liabilities. Current assets are usually inventory, while current liabilities are payable and other accrued liabilities. For the purposes of this exercise, it will be assumed the WCI is equal to zero given the balance sheet of the company where this information is calculated is not available.

It is important to note the value of the firm includes the value of the shareholders and of the lenders. In other words, it includes the money distributed to lenders for debt and the money distributed to the shareholders. Furthermore, if the FCFF is to be estimated, the total amount of money corresponding to the value of the firm needs to be discounted by the weighted average cost of capital (WACC) because it is a debt and equity determination for the shareholders and lenders.

$$Firm\ Value = \sum_{t=1}^{\infty} \frac{FCFF_t}{(1 + WACC)^t} \quad (5)$$

On the other hand, this paper also calculates the value of the shareholders. In this case, it is necessary to subtract the net borrowing from the value of the firm and then discount that amount by the discount rate that reflects the cost of capital to the shareholders, which is the cost of equity.

$$\text{Equity Value} = \sum_{t=1}^{\infty} \frac{FCFE_t}{(1+r_e)^t} \quad (6)$$

Tool calibration

For this TEA, the following assumptions were used to calibrate the tool:

Cost of equity: A 10 % cost of equity is assumed for all scenarios.

Depreciation: This includes all depreciable direct capital costs (DCCs) and indirect capital costs (ICCs) for the nuclear reactors, carbon-capture equipment, and HTSE. These costs are considered over a depreciation period of 15 years using the modified accelerated cost recovery system (MACRS).

Project timeline: The project is assumed to start on January 1, 2030, with a construction period of 1 year for the carbon-capture equipment, HTSE, and SMNR, implying overnight construction. The project lifetime is set at 40 years, based on the SMNR license.

Debt term: 30 years beginning January 1, 2031.

Inflation: No inflation rate is considered in this TEA.

Tax credits: The Inflation Reduction Act (IRA) Section 45 V tax credit is applied for HTSE clean hydrogen production, the IRA Section 45Q carbon-capture credit is applied for the equipment, and the IRA Section 48E tax credit is applied for the SMNR investment tax credits. A more in-depth description of the IRA tax credits is provided in the [supplementary materials](#).

Cost-structure analysis for the individual components: A comprehensive description for each of the assumptions, metrics, and contributors considered for the reference mill plant, the SMNR, and the components in the high-temperature gas-cooled reactor (HTGR) is provided in the [supplementary materials](#).

Results

Nuclear integration with a kraft pulp mill

The reference pulp mill produces 400,000 ADt of unbleached southern softwood pulp annually. The assumed final pulping yield was 46 wt%, which falls within the range of industrial operational yields of 40–55 % [17]. For the purposes of this study, the reference mill produces pulp only, so no papermaking line is included. The reference plant has a robust CHP system that generates electricity while producing the various levels of steam required for the different unit operations. The reference mill was created as a steady-state model from a variety of sources and detailed reports [14]. Only the black liquor boiler and lime kiln were modeled in Aspen Plus; the results are included in the [supplementary materials](#).

The delignification that occurs in the BLRB is necessary for plant operation. Chemical processes that do not convert lignin to CO₂ are also discussed in this section, but for this case it is assumed the recovery boiler must remain. Therefore, nuclear cogeneration aims to reduce the emissions in the reference mill by removing the NG auxiliary boiler and the hog boiler. The bark and fines that would otherwise be burned in the hog boiler would need to be disposed of in some other way.

This analysis is focused on HTGR-type SMNRs. A generic HTGR was modeled in Aspen HYSYS using the generic HTGR stream conditions listed in the [supplementary materials](#). Although high-temperature gas–gas heat exchangers are being developed, it is assumed the steam generator may not be bypassed. In other words, the highest quality of heat accessible from the generic HTGR is the main steam, which has a saturation temperature of approximately 350 °C and is superheated to

565 °C. The generic HTGR is assumed to be available in increments of 200 MWth. Attached to a typical Rankine cycle with a thermal efficiency of about 40 %, electrical production may be 80 MW. Cogeneration, particularly the generation of main CHP steam, will lower the electricity production of the power cycle according to the total amount and grade of extracted heat.

The CHP system in use at the kraft mill attenuates the main steam to the specified HP, MP, and LP conditions required at the plant, cogenerating electricity in the process. The existing CHP system will be leveraged in the case studies wherever possible; the equipment is to be operated on-design. In some cases, the decarbonization systems will require additional energy, which will be supplied by increasing the flow rate of the main steam, operating the CHP off-design. In each case study, the decarbonization opportunities will be analyzed by ensuring the production capacity of the pulp in the mill is unaffected.

In each case, the nuclear-integration design followed these assumptions and limitations.

1. Nuclear-steam integration was implemented in the least-invasive design, meaning tertiary steam generated by the HTGR was injected at the same quality as the boilers it was replacing (500 °C). This process was used to avoid a full thermodynamic analysis of the plant steam systems, given that changes in the injected steam quality could affect heat outputs to other areas of the plant. This type of analysis was performed by Worsham and Terry [24]. However, this method requires condensing main steam from the HTGR in a secondary steam generator to produce tertiary CHP steam for the mill, which is not necessarily the most thermally efficient configuration. A comparison of different integration techniques for this reference plant can be found in Reference [14]. More configurations will be explored in future work.
2. Tertiary steam delivered from the SMNR is injected into the plant's existing CHP system, which can use this steam to generate more electricity. This strategy ensures that steam delivery to plant processes remains unaffected.
3. When nuclear-steam integration was incorporated with the mill, the multifuel boilers were eliminated, including the hog boiler. This assumed that in future work, the waste biomass would be more valuable once converted to bioproducts or liquid fuels. The downside to this assumption is that: (1) there is no current incentive for paper mills to send this material offsite, (2) fewer tax credits would be harvested for CO₂ capture, and (3) in some cases, the elimination of the hog boiler increased the required size of the SMNR.
4. Any additional SMNR capacity that was not used to fulfill plant heat and electricity demands was used to generate electricity sold to the grid.

Other types of advanced SMNRs could be suitable for integration with the reference mill. Notable varieties include liquid–metal, molten-salt, and light-water cooled reactors. Each type has its own advantages. Light-water reactors operate at lower temperatures than the other reactor types; lower-temperature steam would have to be injected into the reference mill's CHP cycle at a header with steam at lower pressure and temperature, or steam-vapor compression would need to be used to boost the temperature and pressure of the steam. HTGR-type SMNRs were selected for this analysis because they can supply the mill with CHP steam without modification.

An Aspen HYSYS model was developed to replace the 90 bar superheated steam lost when decommissioning the hog boiler and the NG auxiliary boiler. The main 165 bar/565 °C steam from the HTGR is required to generate CHP steam at the required conditions. The main steam is split into two paths. A portion heats a secondary steam generator to produce tertiary CHP steam that is sent to the mill, while the remaining portion is sent to the main turbine to generate electricity (see Fig. S7 in the [supplementary materials](#)). By producing the same mass flow rate of steam at the same conditions, the existing CHP equipment

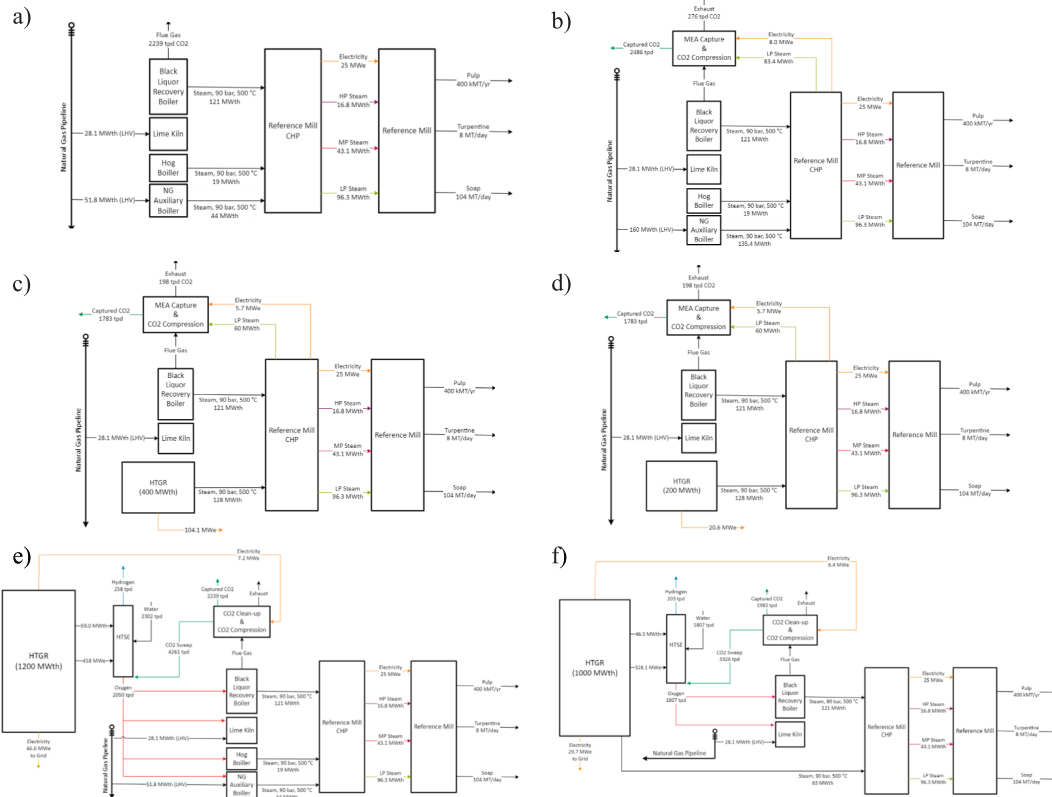


Fig. 3. Utility system and unit operation block flow diagram for: a) BAU kraft pulp mill, LHV designates the lower heating value of the fuel, b) Case 2 – MEA-based CO₂ capture, c) Case 3a – MEA-based CO₂ capture + nuclear-steam integration, d) Case 3b – MEA-based CO₂ capture + nuclear-steam integration, e) Case 4 – oxy-fuel combustion-based CO₂ capture and f) Case 5 – oxy-fuel combustion-based CO₂ capture + nuclear-steam integration.

Table 4
Material, energy balances and tax credits summary for all five case studies. The delta and percent change from BAU is shown in parenthesis.

Material, Energy Balances and tax credits summary for the Case Study						
	Case 1	Case 2	Case 3a	Case 3b	Case 4	Case 5
Description	Baseline (BAU)	MEA-based CO ₂ Capture	MEA-based CO ₂ Capture + Nuclear-steam Integration	MEA-based CO ₂ Capture + Nuclear-steam Integration	Oxy-Fuel Combustion-based CO ₂ Capture	Oxy-Fuel Combustion-based CO ₂ Capture with Nuclear-steam Integration
Inputs						
SMNR Capacity (MWth)	—	—	400	200	1200	1000
NG (MWth)	79.9	188.1 (+108.2, 135.4 %)	28.1 (-51.8, -64.8 %)	28.1 (-51.8, -64.8 %)	79.9 (-79.9, -100 %)	28.1 (-51.8, -64.8 %)
Hog Fuel (MWth)	19	19 (0, 0 %)	0 (-19, -100 %)	0 (-19, -100 %)	0 (-19, -100 %)	0 (-19, -100 %)
Oxygen (tonne/day)	—	—	—	—	2050	1607
Steam Consumed (MWth)	156.2	239.6 (+83.4, +53.4 %)	216.2 (+60, +38.4 %)	216.2 (+60, +38.4 %)	215.2 (+59, +37.8 %)	202.5 (+46.3, +29.6 %)
Electricity Consumed (MWe)	25	33.1 (+8.1, +32.4 %)	30.7 (+5.7, +22.8 %)	30.7 (5.7, +22.8 %)	450.2 (425.2, +1700.8 %)	359.5 (+334.5, +1338 %)
Outputs						
Hydrogen (tonne/day)	—	—	—	—	258	203
Electricity to Grid (MWe)	—	—	104.1	20.6	46.6	29.7
CO ₂ Captured (tonne/day)	—	2486	1783	1783	2239	1982
CO ₂ Emitted (tonne/day)	2239	276 (-1963, -87.7 %)	198 (-2041, -91.2 %)	198 (-2041, -91.2 %)	0 (-2239, -100 %)	0 (-2239, -100 %)
Tax credits considered for SMNR integration at different reactor cost levels (CAPEX \$8,000/kWe, \$5,500/kWe and \$3,000/kWe) during a project lifetime of 40 years						
IRA Tax Credits Supporting Mechanisms	—	PTC 45Q	ITC 48E + PTC 45Q	ITC 48E + PTC 45Q	ITC 48E + PTC 45 V + PTC 45Q	ITC 48E + PTC 45 V + PTC 45Q

can be operated in an identical manner to Case 1 (see Fig. 3 a). This model demonstrates that the required 63 MWth of steam can be produced while cogenerating 51.2 MWe, details can be found in the [supplementary materials](#).

Nuclear-integration opportunities

Case 1: Baseline – BAU scenario

A typical mill does not include any CO₂ capture or mitigation equipment, and only manages emissions based on the EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP) and New Source Performance Standards (NSPS) guidelines. The plant is connected to a pipeline of NG to fuel the auxiliary boiler and lime kiln.

Fig. 3 a depicts the utility requirements for the reference kraft pulp mill. Under normal operation, an auxiliary boiler supplied with NG is required to supplement the main steam produced by the BLRB and hog boiler.

Table 4 provides a comparison of the material and energy balances for Case 1 against the rest of the cases that will be discussed in the following sections. Note that Case 1 only consumes 25 MW of electricity, which is supplied from the plant's CHP system. Because of this, no cases were explored to integrate the plant with nuclear electricity only. The reference mill consumes 129.8 Mt/day NG from the pipeline to supply both the lime kiln and the NG auxiliary boiler and emits 2256 Mt/day CO₂.

Case 2: Conventional CO₂ capture – Monoethanolamine (MEA)-based CO₂ capture

This case focuses on a CO₂ capture process that is commercially available to be implemented in a P&P mill for decarbonization purposes. A large proportion of the CO₂ emissions from the kraft pulp mill come from the BLRB. Demonstrated BLRB decarbonization technologies would require an overhaul of the pulping system or major equipment investments. Theoretically, the plant could reduce its CO₂ footprint by switching to 100 % renewable fuels, but this option would not have much of an effect on the actual CO₂ emissions of the plant and would not harvest any credits from the IRA. Rather, the least capital-intensive option with an immediate return on investment is adding a carbon-capture system to sequester the emissions.

Monoethanolamine (MEA)-based CO₂ capture is a commercially available option to capture CO₂ emitted from a point source. This is likely the most attractive near-term option for decarbonization in the P&P industry because a capture system can be powered by any fuel source, and the P&P mills can take advantage of the Section 45Q tax credit for carbon sequestration. Case 2 describes the system changes and resulting revenues using the NG auxiliary boiler to power the MEA capture and compression unit. As discussed in the next section, Case 3 is essentially the same configuration, but with a nuclear power plant providing steam and electricity to the unit instead through the plant's CHP system.

Fig. 3 b depicts the addition of MEA-based CO₂ capture to the reference mill. The MEA carbon-capture system results in 90 % CO₂ recovery and requires 2.9 GJ/Mt-CO₂ to be captured in LP steam. The captured CO₂ is compressed and liquefied to be transported to long-term storage, further requiring 77.8 kWh-e/Mt-CO₂. The added requirements in this case must be supplied by increasing the duty of the NG auxiliary boiler, which slightly increases the overall total of CO₂ that goes to the MEA capture system.

The energy and material balances for the carbon-capture case using an NG auxiliary boiler is presented in Table 4. This case uses more than double the NG required for Case 1 and generates more CO₂. However, the implementation of the carbon-capture system decreases the overall emitted CO₂ by 88 %.

Case 3: MEA-based CO₂ capture + nuclear-steam integration

This case contains two subcases that compare the results of the same

system with a 200-MWth HTGR size system and a 400-MWth size system. Originally, this case only used the 400-MWth design, but the desire to analyze a smaller HTGR was investigated, so the thermal integration was lowered for another case to 200 MWth.

Case 3a: 400-MWth HTGR. Fig. 3 c demonstrates that a 400-MWth HTGR can be used to replace the hog boiler and NG auxiliary boiler, reducing the NG usage and CO₂ emissions that need to be captured. The 90 bar, 500 °C steam that the reference mill CHP requires must be generated by the main 165 bar, 565 °C steam from the HTGR. Although the main steam extraction for this case is only 128 MWth, a 200-MWth unit was not used in this configuration because the mixture of the main condensate and the turbine cycle condensate would be too hot to cool the primary HTGR coolant unless heat is wasted. An alternative integration strategy allowing a 200-MWth reactor to be used is shown in Case 3b. Nuclear-steam integration reduces the NG usage to only that required by the lime kiln, reducing the overall CO₂ emissions and CO₂ captured.

Table 4 provides the energy and material balances for Case 3a. NG usage is reduced from the baseline because the multifuel boilers are eliminated. This case reduces the overall CO₂ produced by the mill and reduces the total emitted CO₂ by 91 %. Note this is a slightly higher reduction than observed in Case 2 because the same percentage of CO₂ is captured by the MEA system, but the total CO₂ that is produced is slightly less because the energy for capture is coming from a non-carbon-emitting fuel.

Case 3b: 200-MWth HTGR. Fig. 3 d demonstrates that a 200-MWth HTGR can also be used to replace the hog boiler and NG auxiliary boiler as in case 3.a, similarly reducing NG usage and capturable CO₂ emissions. Likewise, as done in case 3.a, the 90 bar and 500 °C steam required by the reference mill is generated by the HTGR main steam (165 bar and 565 °C). Unlike the 400-MWth HTGR in Case 3a, a larger percentage of the main steam is extracted for thermal use in this case. As a result, the condensate from this process steam generator needs to be further cooled to 268.5 °C before mixing with the turbine condensate. This cooling process is managed by using the condensate to reheat the turbine interstage, involving waste heat of 10 MWth. Thus, the 400-MWth HTGR operates within a more conventional and efficient setup but is oversized for the application and heavily relies on selling excess electricity. These two cases were created to evaluate the process implications, performance and economic benefits of integrating nuclear steam from high-temperature gas-cooled reactors (HTGRs) of different capacities—400-MWth and 200-MWth—into the mill's energy system for enhanced flexibility, and efficiency in reducing natural gas usage and CO₂ emissions.

Table 4 gives the energy and material balances for Case 3b, which mainly differs from case 3a on the net electricity export capacity, translated into less revenue but also using a smaller HTGR and a lower CAPEX. NG usage is reduced from the baseline because the multifuel boilers are eliminated. This case reduces the overall CO₂ produced by the mill and reduces the total emitted CO₂ by 91 %. Note this is a slightly higher reduction than observed in Case 2 because the same percentage of CO₂ is captured by the MEA system, but the total CO₂ that is produced is slightly less because the energy for capture is coming from a non-carbon-emitting fuel. A detailed description of case 3b variation and its trade-offs on the overall economics (cumulative NPV) is described in a dedicated section (3.4) for economic assessment and feasibility study of all case studies and also seen on Fig. 5.

Case 4: Oxy-fuel combustion-based CO₂ capture

As an alternative to the MEA-based CO₂ capture process, an oxy-fuel combustion system, as shown in Fig. 3 e, has been studied. Oxy-fuel combustion, unlike air-firing, produces a flue gas with a very high CO₂ content that has lower associated sequestration costs. For the

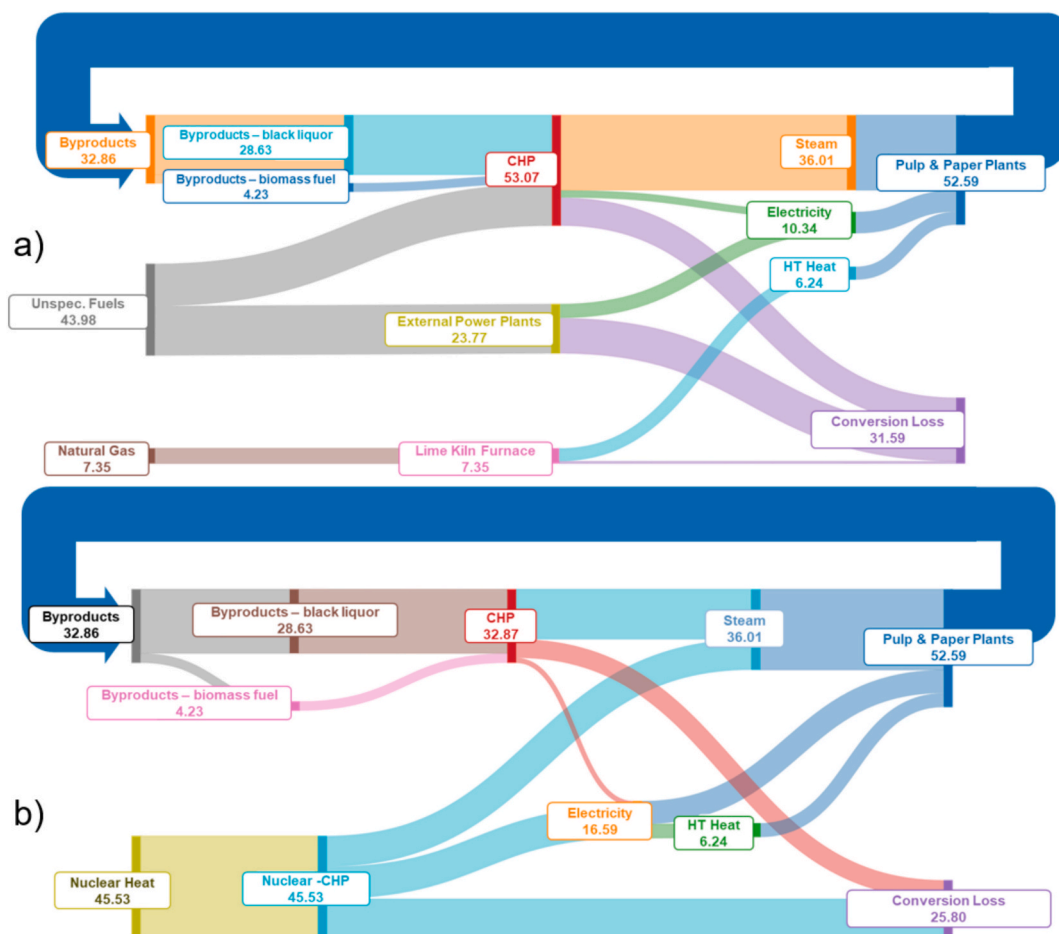


Fig. 4. Sankey diagram of (a) the energy demand and supply on a national level for the P&P industry, and (b) the potential for a nuclear-integrated scenario in the energy demand and supply on a national level for the P&P industry.

purposes of this study, the O_2 is supplied by HTSE, where the O_2 electrode is swept by a recycled portion of the CO_2 product to produce an air analog that is 40-mol% O_2 and 60-mol% CO_2 . A model was developed in Aspen HYSYS to couple such an HTSE stack to a 1200-MWth HTGR-type SMNR, where nuclear heat and electricity are used to split water into an oxygen and hydrogen byproduct.

Fig. 3 e depicts the nuclear-integration schematic for the oxy-fuel combustion in the BLRB, lime kiln, hog boiler, and NG auxiliary boiler. The only difference between this case and the BAU operation shown in Case 1 is that the combustion equipment is fired by a blend of CO_2 and O_2 rather than normal air, yielding a flue gas devoid of N_2 . The flue gas can be cleaned up simply by using existing emission controls at the mill (e.g., venturi scrubber, electrostatic precipitator) and a stack condenser to remove combustion water. A portion of the CO_2 is recirculated to the oxygen electrode of the HTSE stack, while the surplus is compressed and liquefied. Because the electricity for compression is supplied by the HTGR, the reference mill CHP can be operated on-design.

Table 4 also summarizes the material and energy balances for Case 4. In this case, 258 Mt/day of hydrogen is produced as a byproduct, and very little of it can be used onsite. This hydrogen must be transported to another location, or, ideally, used nearby in an energy park application. A potential synergistic approach would be to send both the hydrogen byproduct and the captured CO_2 to a nearby synfuel plant. This decarbonization pathway also reduces the CO_2 emissions of the kraft mill to essentially zero.

Case 5: Oxy-fuel combustion-based CO_2 capture with nuclear-steam integration

Fig. 3 f, depicts a similar schematic as the one presented in Fig. 3 e, except the HTGR supplies steam to the CHP system. The hog boiler and NG auxiliary boiler are removed, reducing the oxygen demand and allowing a 1000-MWth HTGR to be used, as opposed to the 1200-MWth HTGR in Case 4, which reduces the total investment. A total of 203 Mt/day of hydrogen is produced as a byproduct, which similarly must be sold to a nearby hydrogen consumer.

Table 4 summarizes the material and energy balances for Case 5. As in Case 4, Case 5 eliminates virtually all CO_2 emissions from the mill. In addition, because the HTGR supplies steam rather than oxygen for the multifuel boilers, the energy requirements of the system are reduced.

The energy balances in Table 4, shows significant variations across the five cases. In terms of natural gas (NG) consumption, Case 1 (BAU) has a value of 79.9 MWth. In contrast, Case 2 sees a dramatic increase to 188.1 MWth (+135.4 %) when the NG auxiliary boiler is used to power the MEA capture and compression unit. Cases 3a and 3b, both utilizing MEA-based CO_2 capture with nuclear-steam integration, show a significant reduction in NG consumption to 28.1 MWth (−64.8 %), indicating the efficiency brought by using a non-carbon emitting energy source to power carbon capture equipment. Case 4, which employs oxy-fuel combustion-based CO_2 capture, where the air analog of 40 mol% oxygen and 60 mol% CO_2 is used to fire up the NG auxiliary boiler results on a CHP operating on design conditions using the baseline NG requirements, and Case 5 maintains the reduced NG consumption of 28.1 MWth (−64.8 %). Steam consumption also varies, with the highest increase seen in Case 2 at 239.6 MWth (+53.4 %) compared to the baseline



Fig. 5. NPV cumulative cash-flow outcomes for all TEA scenarios in 2022 USD.

of 156.2 MWth. Cases 3a, 3b, 4, and 5 show a more moderate increase in steam consumption, ranging from + 29.6 % to + 38.4 %, highlighting the additional steam requirements for CO₂ capture processes.

The carbon emissions and capture data seen in Table 4, reveal the effectiveness of each case in reducing CO₂ emissions. Case 1, the baseline scenario, emits 2239 tonnes of CO₂ per day. Case 2 shows a significant reduction in emissions to 276 tonnes per day (-87.7 %) due to the MEA-based CO₂ capture process. Cases 3a and 3b further reduce emissions to 198 tonnes per day (-91.2 %), benefiting from the integration of nuclear steam. Cases 4 and 5, which utilize oxy-fuel combustion-based CO₂ capture, achieve zero emissions (-100 %). In terms of CO₂ capture, Case 2 captures 2486 tonnes per day, collecting the most 45Q credits among all cases. Cases 3a and 3b both capture 1783 tonnes per day, while Cases 4 and 5 capture 2239 and 1982 tonnes per day, respectively. These values indicate that while oxy-fuel combustion-based systems are highly effective in reducing emissions to zero, MEA-based systems with nuclear integration also achieve substantial capture efficiencies.

The electricity consumption data highlights the increased energy demands of CO₂ capture technologies. Case 1 consumes 25 MWe, while Case 2 sees a rise to 33.1 MWe (+32.4 %). Cases 3a and 3b consume slightly less electricity at 30.7 MWe (+22.8 %). However, Cases 4 and 5 show a dramatic increase in electricity consumption, with Case 4 consuming 450.2 MWe (+1700.8 %) and Case 5 consuming 359.5 MWe (+1338 %). This increase is directly caused by the energy intensive HTSE process, which is used for oxygen production. In terms of electricity production, Case 3a produces 104.1 MWe, the highest among all cases. Case 3b produces 20.6 MWe, while Cases 4 and 5 produce 46.6 MWe and 29.7 MWe, respectively. These electricity surpluses are artifacts of the discrete availability of HTGR type SMNRs, in increments of 200 MWth. While they constitute additional revenue, this may not always be optimal. In a market scenario where the effective levelized cost of electricity is greater than the wholesale electricity price available on the grid, electricity sales represent a net loss; it would theoretically be advantageous to size the SMNR to the exact size required by the mill and

eliminate grid export. Conversely, if electricity could be sold at a net gain, such as in a scenario with low nuclear CAPEX and high tax-credit capture, it would even be viable to oversize the SMNR and increase the surplus electricity. Overall, the trends suggest a trade-off between achieving lower emissions and managing increased energy demands, highlighting the importance of optimizing these systems for maximum efficiency. The tax credits applied on each case can be also seen in Table 4, a dedicated section providing a detailed explanation of each type and its pertinence and relevance to each case is presented later in the paper.

National potential for nuclear-integration options in P&P plants

National demand has been estimated from the data in Reference [25]. Since this data combines the entire forest product industry, estimates for the P&P industry were separated using the breakdown of the demands for subsectors in Reference [26] and fuel demand assessing all the black liquor content of the fuel belonging to the P&P industry. This analysis assumes that all P&P mills are using CHP systems rather than stand-alone boilers being used in other, more distributed, and smaller single-point-demand subsectors. This simplifies energy demands and their supply to a national level, as shown in Fig. 4 a. External fuels coming into onsite CHP and external power plants is mostly NG within the U.S., but other fuels are possible. Conversion efficiencies also are adopted from Reference [25]. While the reference plant for nuclear-integration options only included pulping operations, the estimates for national potential include all U.S. pulping and papermaking operations (e.g., paper mills, paperboard mills, newsprint mills, pulp mills, integrated mills).

Case 1 was the baseline scenario assumed for the national potential, seen in Fig. 4 a. The nuclear-integrations scenario showcased in Fig. 4 b substitutes all fossil fuel demands for clean nuclear energy. The reference integration model was modified for the national average plant with a new ratio between externally required electricity and steam. The reactor output was modified to provide exactly the energy requirements

of the plant, for zero electricity exports after meeting additional electricity demand for an electrified lime kiln. As for other industries, electrifying the lime kiln assumes eliminating stack energy losses. The Sankey diagram for this approach on a national potential level is shown in Fig. 4 b. Since new nuclear CHP is predicted to have significantly higher efficiency than the ones currently used in aging systems, overall conversion loss is reduced by almost 6 GW of primary energy. A similar—or even higher level—of primary energy savings is attainable through plant modernization and implementation of energy-efficient solutions and waste heat recovery systems, rather than from a nuclear-integration option.

The nuclear-integration scenario adopted for the potential on a national level effectively reduces all non-biogenic CO₂ emissions. With an assumption that all external fuel is NG and biomass fuel has zero net emissions, the proposed nuclear-integration option has the potential of reducing CO₂ emissions by 73 Mt/yr, with a breakdown for each type of energy provided in the [supplementary materials](#).

Economic assessment and feasibility study

This paper presents a comprehensive technoeconomic assessment of the integration of advanced nuclear reactors into a pulp and paper mill, considering financial incentives from the Inflation Reduction Act (IRA) of 2022. The IRA introduced several tax credits aimed at supporting clean energy, including nuclear power, by incentivizing both existing and new projects through financial mechanisms that reduce operational and capital expenditures costs. For new nuclear projects, particularly advanced reactors placed into service in 2025 or later, developers can choose between a technology-neutral production tax credit (PTC) under section 45Y, offering up to \$25 per megawatt-hour for the first ten years of operation (adjusted for inflation), or an investment tax credit (ITC) under section 48E, providing up to 30 % of the project qualified investment costs—though only one can be applied per facility. Additionally, Section 45 V of the Internal Revenue Code, introduced by the IRA, established the Clean Hydrogen Production Tax Credit, which incentivizes the production of low-emission hydrogen at qualified facilities. Finally, Section 45Q provides the credit for Carbon Oxide Sequestration, which was expanded by the IRA to encourage carbon capture, utilization, and storage (CCUS). Details of the IRA tax credits are provided in the [supplementary materials](#).

Compared with Case 1, the five key cost and revenue drivers for the mill are the CAPEX of the nuclear power plant which also affects the benefits from Section 48E tax credit, the CO₂ captured (Section 45Q tax credit), the amount of hydrogen produced (Section 45 V tax credit), the NG purchased, and the excess electricity from the SMNR capacity that can be sold to the grid. The product-related feedstock expenses and product outputs are assumed to be the same for all cases. The results seen in Fig. 5 shows that most of the scenarios reach a net present value (NPV) higher than Case 1 as the capital costs of nuclear reactors go down, heavily impacted by the tax credits (ITC 48E, PTC 45 V or PTC 45Q) mechanism claimed.

For instance, Case 2 only evaluates the impact of PTC 45Q through conventional MEA CO₂ capture; when it is compared with Case 3 variations, it is seen to be more profitable at high and moderate reactor cost levels than Case 3 which accounts for nuclear expenditures, as Case 2 is a non-nuclear CO₂ capture scenario not sensitive to nuclear CAPEX. This trend is reversed when reactor costs are low by leveraging PTC 45Q. For high nuclear capital costs (\$8,000/kWe), only Case 2 is more profitable than Case 1, as it is a non-nuclear CO₂ capture scenario not impacted by sensitivity to nuclear CAPEX. When learning progresses such that moderate capital costs of around \$5,500/kWe are obtained, Cases 3a, and 3b also become more profitable than Case 1. Finally, if capital costs fall to \$3,000/kWe, all scenarios are more profitable than Case 1. It is important to note that these results are only relevant for this specific mill configuration and the specific assumptions taken in the TEA. These results should not be applied generally to U.S. P&P mills. However, these

results do help us to understand the economic drivers behind the next-generation reactor integration pathways accounted in this study. A descriptive section of the mechanisms applied on each case can be seen in Table 4. Note that the high variability in capital costs (\$8,000/kWe–\$3,000/kWe) stems from differing assumptions about technological innovation, learning rates (LR), and deployment scales, as outlined in Abou-Jaoude et al. 2024 [27]. In the most competitive scenario, the low capital cost of \$3,000/kWe is the result of breakthrough advancements combined with high LR (up to 12 % per doubling of capacity) and aggressive deployment (e.g., 200 GW by 2050) which drive steep cost reductions. On the other side, the conservative scenario (\$8,000/kWe) assumes incremental improvements based on historical trends, lower LR (around 5 %) and modest deployment (e.g., 34 GW by 2050), resulting in slower cost declines and higher 2050 overnight capital cost values.

NPV

Using the NIHPA and SET tools, the five previously described scenarios are modeled to obtain the present cash-flow value for each of the five potential mill decarbonization pathways. Cash-flow growth is calculated using Equation (7).

$$\text{Cash Flow Growth} = \frac{NPV_{\text{case}_i} - NPV_{\text{BAU}}}{NPV_{\text{BAU}}} \quad (7)$$

The results for each scenario, considering the three different CAPEX levels with and without tax credits, are summarized in Fig. 5. The findings indicate that SMNR CAPEX is the primary cost driver affecting the difference in NPV profits between scenarios. The selected tax credits (e.g., ITC-48E, PTC-45 V, and PTC-45Q) serve as the main revenue driver in each scenario.

It is important to note that the PTC-45 V tax credit for hydrogen production, used in this study does not include the latest IRA update from January 2025 [28]. However, since all the scenarios under study assumed the construction of new reactors, the incrementality requirement for hydrogen production—which necessitates new energy sources to divert energy to the hydrogen plant from the latest update—is met and does not affect the results. In other words, the PTC-45 V is assumed to be as described in the IRA note from December 2023 [29].

With the tax credits, Case 2 always has a higher NPV cash-flow than Case 1. This confirms the important assumption of this study that biogenic and non-biogenic CO₂ emissions be treated and captured equally. This result suggests that even without a nuclear-integration option, implementing CO₂ capture at existing kraft pulp mills by 2030 may be a profitable business decision. These results should be confirmed on an individual basis for each mill.

The highest NPV cash-flow scenario was Case 3a, with tax credits ITC-48E and PTC-45Q and low-capital costs. Case 3a, which has the same carbon-capture system as Case 2 but is powered by nuclear instead of NG, has a higher NPV than Case 1 and Case 2 with tax credits and a low-capital cost. However, if capital costs fail to achieve these low levels, the NPV for the capture system powered by nuclear in Case 3a is lower than that for NG in Case 2. This suggests that a carbon-capture system powered by NG may be equally cost-effective or more cost-effective than one powered by nuclear due to lower total capital investment along with the fact that it produces its own CO₂ to capture, boosting tax credit collection.

Importantly, the tax credits reduce the net investment costs and make all nuclear-integration scenarios (i.e., Cases 3, 4, and 5) more cost-competitive than Case 1 when low capital costs are achieved (\$3,000/kWe). With high-capital costs and without tax credits, there are no scenarios that have a higher NPV than Case 1.

Cases 3a and 3b investigate some of the drivers behind this competitiveness. In Case 3a, a 400-MWth reactor is used, while in Case 3b, a 200-MWth reactor is used. The tradeoff is that the 200-MWth has less excess electricity available to sell to the grid (about 80 % less than

Case 3a). When capital costs are only \$3,000/kWe, the 400-MWth scenario has a higher NPV. As capital costs rise, the 200-MWth scenario has a higher NPV. The only difference between these two cases is the reactor capital cost and revenue from the exported electricity. This suggests that in addition to the capital cost, the relationship between electricity revenue and the effective cost to produce surplus electricity is also a major cost driver. In the low-capital cost scenario, the 400-MWth case has a higher NPV with and without tax credits, meaning the additional electricity sold is making up for the additional investment. In the high-capital cost scenario, the 200-MWth case is more competitive because it requires less initial capital investment and does not necessitate selling as much surplus electricity at a loss. This result, however, is specific to the high-electricity prices in the region and may change in a different location. This result is important because: (1) it suggests that investing in more capacity spread across several markets and commodities can help recoup initial investments, and (2) it strengthens the argument for utilities to own and operate reactors for the grid and contract a portion of their capacity to industrial customers.

Between the two oxy-fuel combustion configurations, Case 5 always has a higher NPV than Case 4. Case 5 eliminates a significant portion of the combustion duty, increasing profitability by collecting similar tax credits with a smaller capital investment in the HTSE and SMNR (i.e., 1000 MW for Case 5 compared with 1200 MW for Case 4). Case 4, however, has a larger demand for oxygen, and therefore produces more hydrogen as a byproduct. This indicates that for this configuration, the capital cost of the reactor is driving the NPV more than the hydrogen production credit. However, Case 5 is extremely sensitive to the capital cost of the SMNR and the availability of tax credits. In all scenarios except for the low-capital costs with tax credits, Cases 4 and 5 have the lowest NPV of all cases, while in the highest-capital cost scenario, a negative NPV is generated, meaning the total costs of the project were greater than the revenues. If, in addition to the 45 V hydrogen PTC, a buyer could be found who is willing to pay a premium for clean hydrogen, the economic performance of Cases 4 and 5 could be improved.

Additionally, if multifuel boilers were inserted back into the thermal systems, more total CO₂ would be captured, increasing the share of positive NPV from harvested Section 45Q tax credit. However, the results comparing Cases 4 and 5 show that the increased tax credit collection does not overcome the CAPEX required to build the additional nuclear reactor required to power the CO₂ capture equipment. In future work, these cases will be explored more thoroughly. Fig. 5 provides a comparison of the NPV cumulative cash-flow outcomes for all TEA scenarios in U.S. dollars (USD).

Conclusions

This study demonstrates that integrating the U.S. P&P industry operations with SMNRs can significantly enhance process efficiency and reduce CO₂ emissions by supplying clean electricity and heat for both the mill and for CO₂ capture systems. By analyzing five different scenarios, we found that substituting traditional fuel sources with clean nuclear energy can meet the industry's thermal and electrical demands, notably reducing non-biogenic CO₂ emissions by up to 73 Mt/yr as revealed on the national-level analysis.

The P&P industry's thermal requirements, typically met by natural gas and biomass combustion, can be effectively supplied by SMNRs, providing steam to CHP headers. This integration opens opportunities for producing electricity, steam, clean hydrogen and oxygen, and leveraging byproducts like biomass and black liquor for other biobased products and chemicals.

Key process units and blocks such as HTSE, CHP, and MEA CO₂ capture show significant potential for decarbonization, especially when supported by tax credits. Comparative analysis of MEA CO₂ capture and oxy-fuel combustion reveals MEA CO₂ technology as the most promising decarbonization pathway, especially when fueled by nuclear power.

Similarly, the inclusion of tax credits is crucial for making these options profitable.

Our analysis indicates that nuclear integration, especially when leveraging low capital costs and tax incentives, potentially increases the NPV of the mill and could cover decarbonization costs through additional revenue streams. These insights suggest that while specific configurations need further exploration, nuclear power presents a promising pathway for either energy addition or transformation in the P&P industry.

Overall, the results of this study were specific to a single reference mill case, and we should be cautious about making overall claims about the prospects of nuclear to be cost-effective for the P&P industry; however, these findings illuminate the cost and revenue drivers for decarbonization and nuclear-integration opportunities. If pulp mills are decarbonized using nuclear power, it may be advantageous to do so by entering joint ventures with neighboring facilities. Regardless, pulp mill operators should consider investing in carbon-capture equipment to harvest the tax credits, with or without integrating nuclear power. Future work is imperative to assess the results of such integration for a variety of mill configurations and include other decarbonization pathways that might be coupled with SMNRs.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.seta.2025.104582>.

Data availability

Data will be made available on request.

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