INL/RPT-23-75960-Revision-0

Generic Model for Pulp and Paper Production in the United States

December 2023

Changing the World's Energy Future

Elizabeth Kirkpatrick Worsham, Samuel Jacob Root, Eliezer Antonio Reyes Molina, Kathleen Patricia Sweeney

Idaho National Laboratory

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Integrated Energy Systems

M4CT-24IN1203056: Generic Model for Pulp and Paper Production in the United States

December 15, 2023

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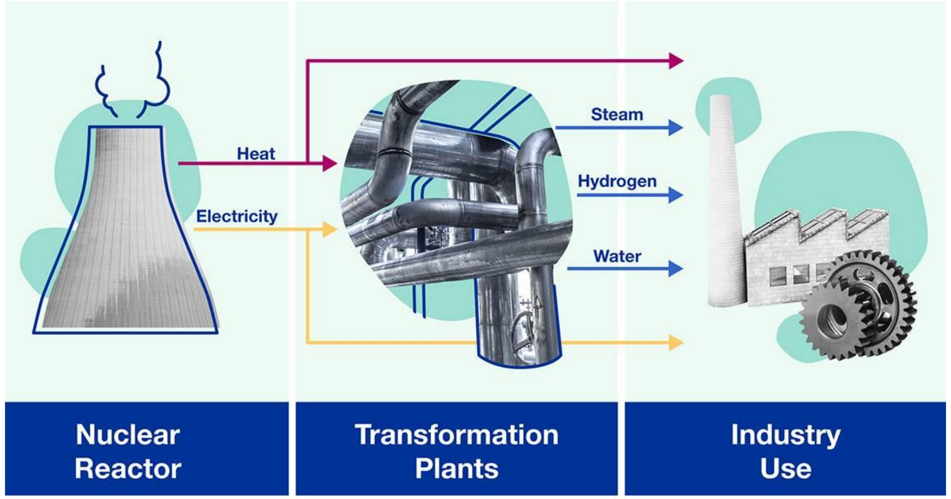
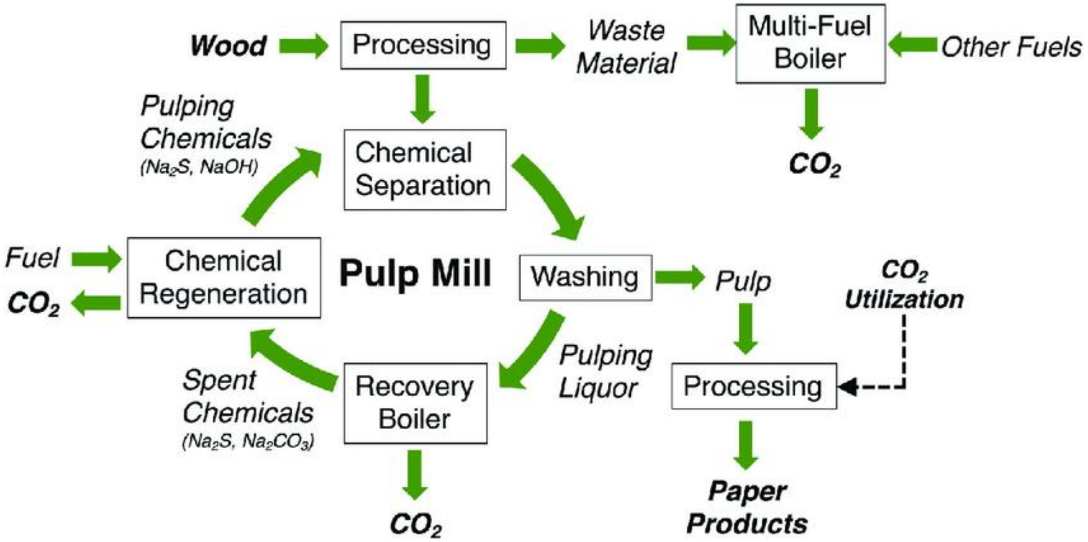
Advanced Nuclear Reactors Integration with a Ref. Kraft Pulp Mill

Integrating advanced nuclear reactors into the pulp and paper (P&P) industry is a concept explored to enhance the efficiency and sustainability of the pulping and paper making process. Nuclear reactors can provide process heat and power for various process operations.



Pulp and Paper



Sagues et al. 2020

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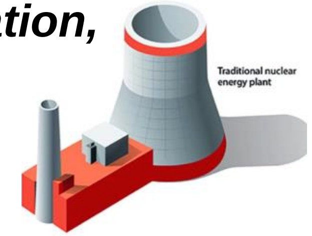
Key Points to Consider by Integrating Advanced Nuclear Reactors

- ✓ **Cogeneration of Heat and Power:** The heat can be used directly in the P&P manufacturing process, such as in the digestion and drying stages.
- ✓ **Steam Production:** Many P&P processes require high-pressure steam for various purposes, including cooking wood chips, concentrating black liquor, drying paper, and powering turbines.
- ✓ **Carbon Neutrality:** Nuclear power does not produce greenhouse gas (GHG) emissions during electricity generation. By integrating nuclear power, pulp and paper mills can reduce their carbon footprint.
- ✓ **Reliability and Stability:** Nuclear energy provides a stable and reliable source of power, reducing the risk of production interruptions due to power in continuous manufacturing processes like paper production.
- ✓ **Cogeneration:** Heat from advanced nuclear reactors can be used directly or recovered after electricity is generated
- ✓ **Cost Considerations:** The cost of advanced nuclear technologies can be substantial, but long term, nuclear power can offer competitive electricity and heat production costs.

Thus, nuclear energy integration reduces the reliance on fossil fuels for process heat and power, making the pulp and paper making process more energy-efficient, while reducing carbon and greenhouse gas emissions. This can improve the stability and economics of P&P industry operations.

Therefore, pulp mills need to assess the economic feasibility of integration, considering construction, operation, and maintenance costs.



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Objectives and Goals

Objectives

Develop reference plant designs for advanced nuclear reactors of various designs integrated at a reference Kraft Pulp Mill and assess the techno-economics. Including:

1. Conversion of black liquor recovery boiler to an oxy-fired boiler and lime kiln to oxy-fired or electric
2. Substitution of thermal duties with advanced-reactor heat
3. Diversion of black-liquor and woody biomass to new chemical conversion unit to produce chemicals or biofuels

Objectives and Goals

Goals

➢ Using the standard financial assessment tool, perform a technoeconomic analysis (TEA) for integration of nuclear integration with a pulp and paper mill in consideration of:

- Substitution of nuclear energy for conventional energy supply
- Avoided cost of emissions reduction
- Schedule for advanced reactor construction and implementation
- Capital costs, engineering costs, etc.
- Gaps of technology development and demonstration
- Schedule for licensing and permitting
- Concepts of operations (including labor)

➢ Develop oxy-fired models for the lime kiln and black-liquor recovery boiler

➢ Assess the feasibility of alternatives to black-liquor combustion (such as gasification) to produce syngas in place of combustion in a black liquor recovery boiler.

Benefits to Industry

- Provide the P&P industry with design options and technoeconomic results for decarbonization of pulp and paper production using clean nuclear energy.
- Follow-on and parallel projects include carbon capture and utilization for producing synthetic transportation fuels (MeOH) and chemicals.
- Reference plant designs will serve as a design basis that can be shared with reactor vendors and various industries to pave the way for advanced reactor demonstration and deployment.

Kraft Pulp Plant Capacities and Distribution

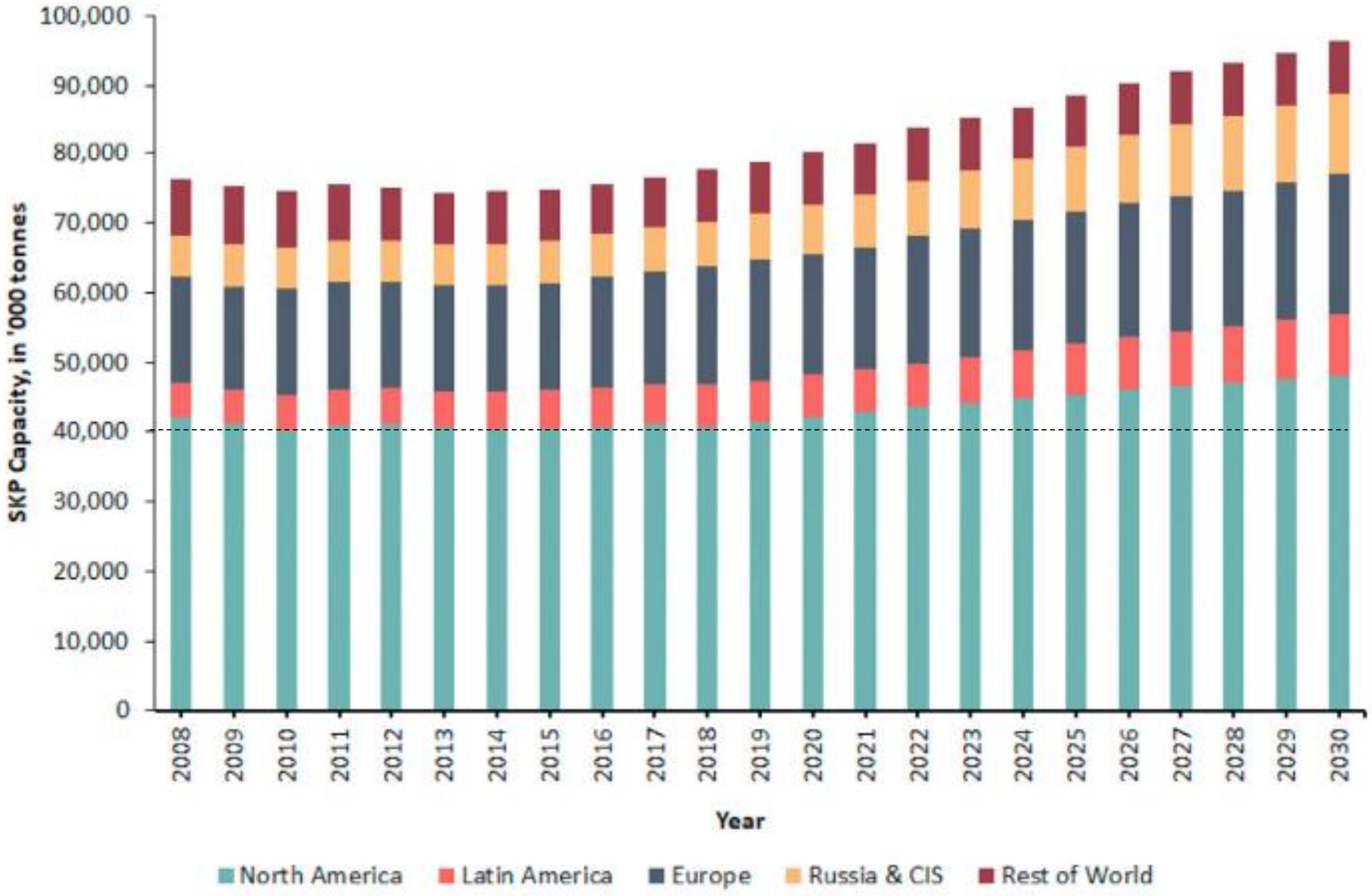
Design Basis - Generic Ref. Kraft Mill Plant

Assumptions:

- Domestic chemical pulp production from FAO 2023 = 44,014,000 ADt/yr
- Percentage of USA plants that are kraft Mills = 80%
- 85 USA kraft Pulp Mills
- Assuming that each kraft pulp mill has around the same capacity, the selected capacity for a reference kraft pulp mill is around 400,000 ADt/yr
- About 80% of the nation's kraft mills run over the reference capacity, while 31% of the total mills are ±100,000 ADt/yr the pulp plant reference capacity.
- Reference mill capacity: does not exceed more than 2 pulp/paper machines

(Food and Agricultural Organization (FAO) of the United Nations 2023)

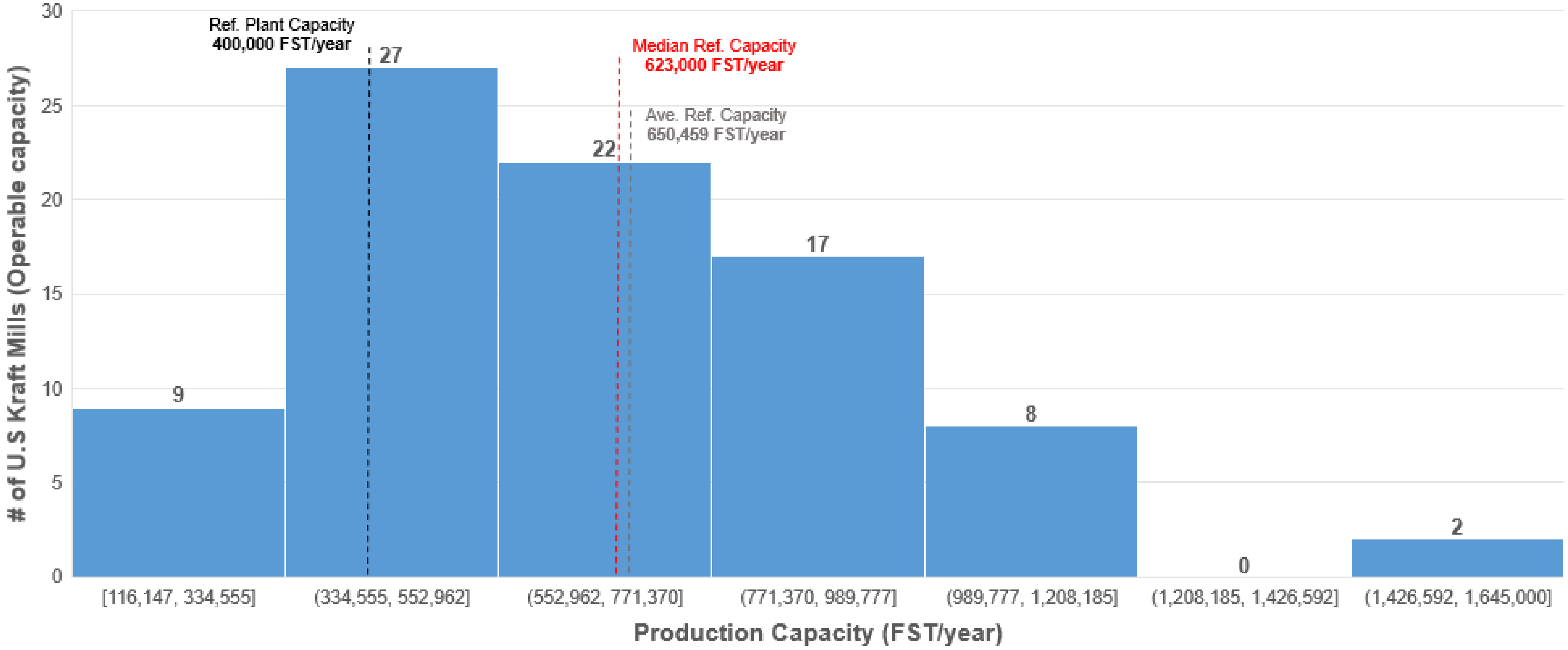
Global Softwood Kraft Pulp Capacity 2008 to 2030



(Aryan and Kraft 2021)

U.S Softwood Kraft Mill Plant Capacities Distribution

~ 42% of the U.S Kraft Mills are covered under the reference capacity



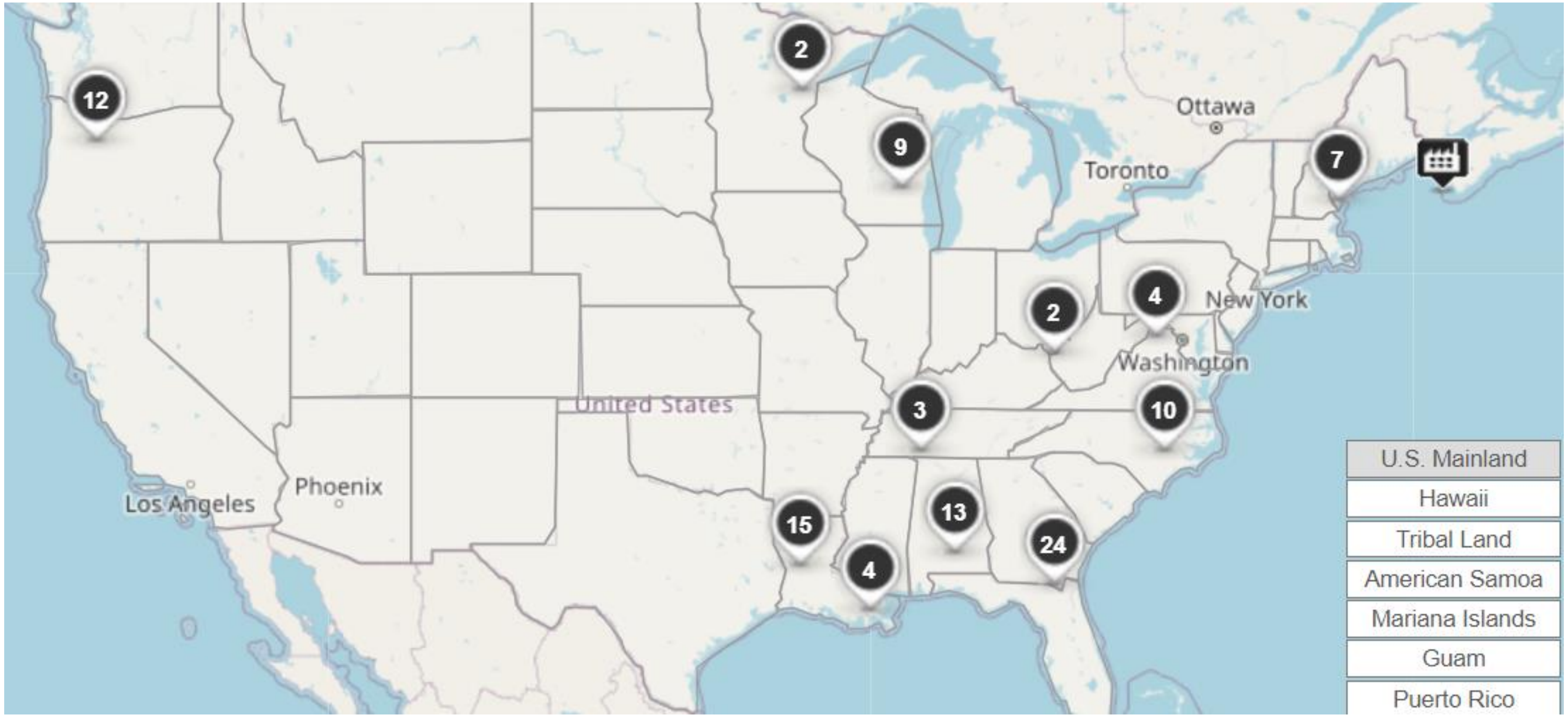
(Fisher International 2023)

(U.S. EPA Office of Atmospheric Protection 2023)

U.S Pulp and Paper Mills Locations

These are the state-specific locations of 105 operating pulp mills in the United States, 80% are Kraft pulping

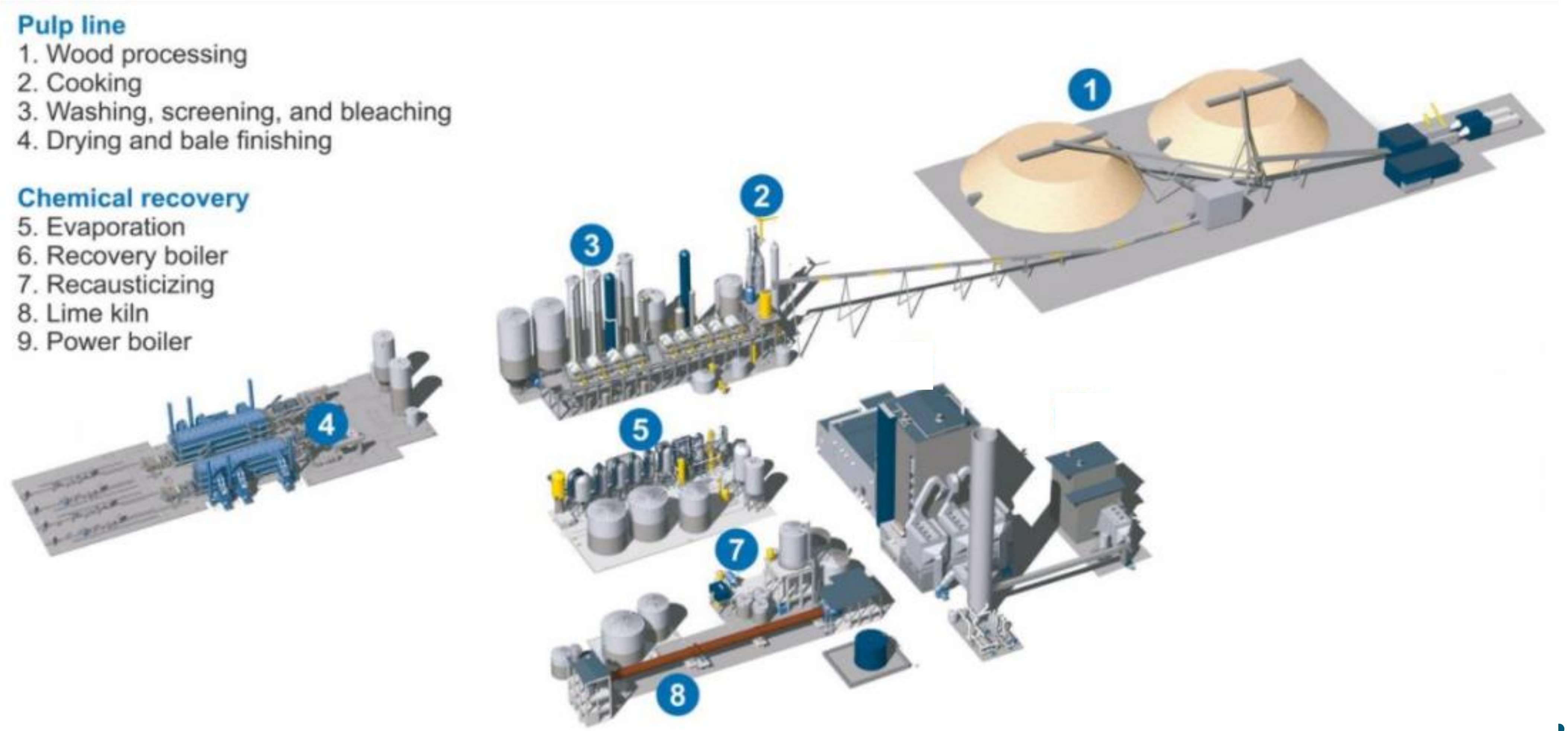
Most of the Kraft mills are in the Southeast U.S due to biomass feedstock availability



(U.S. EPA Office of Atmospheric Protection 2023)

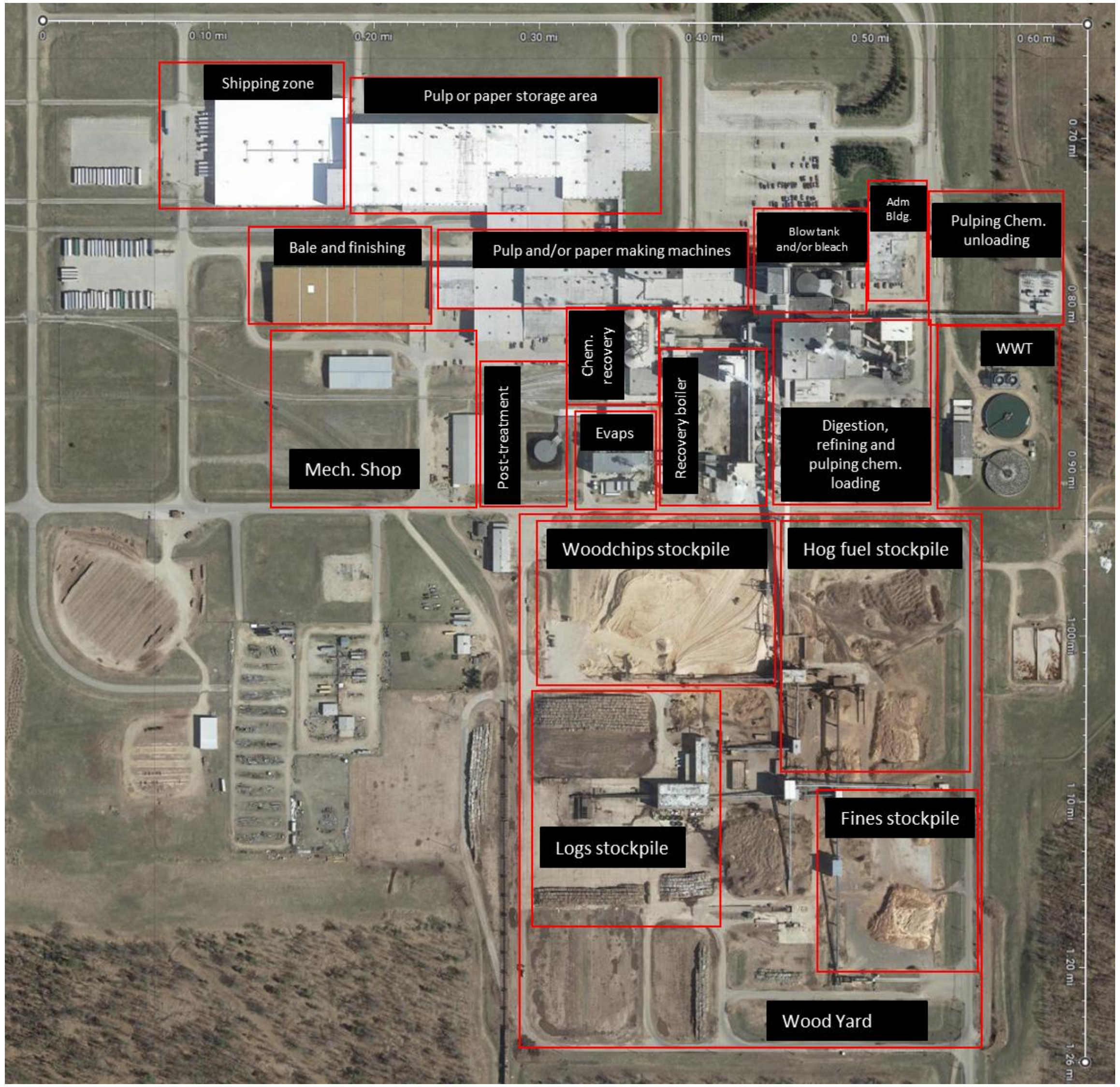
Kraft Pulp Plant Overview: Material and Energy Balances

Visual Representation of an Integrated Kraft Pulp Mill



(Andritz nd.)

Kraft Mill Overhead Components Identification



About 3380 ft ~ 0.64 miles ~ 1.02 Km of Length and Width

Area (L x W) = 0.41 square miles ~ 1.143e+7 square ft ~1 .06 square Km

Image Source: Google Maps

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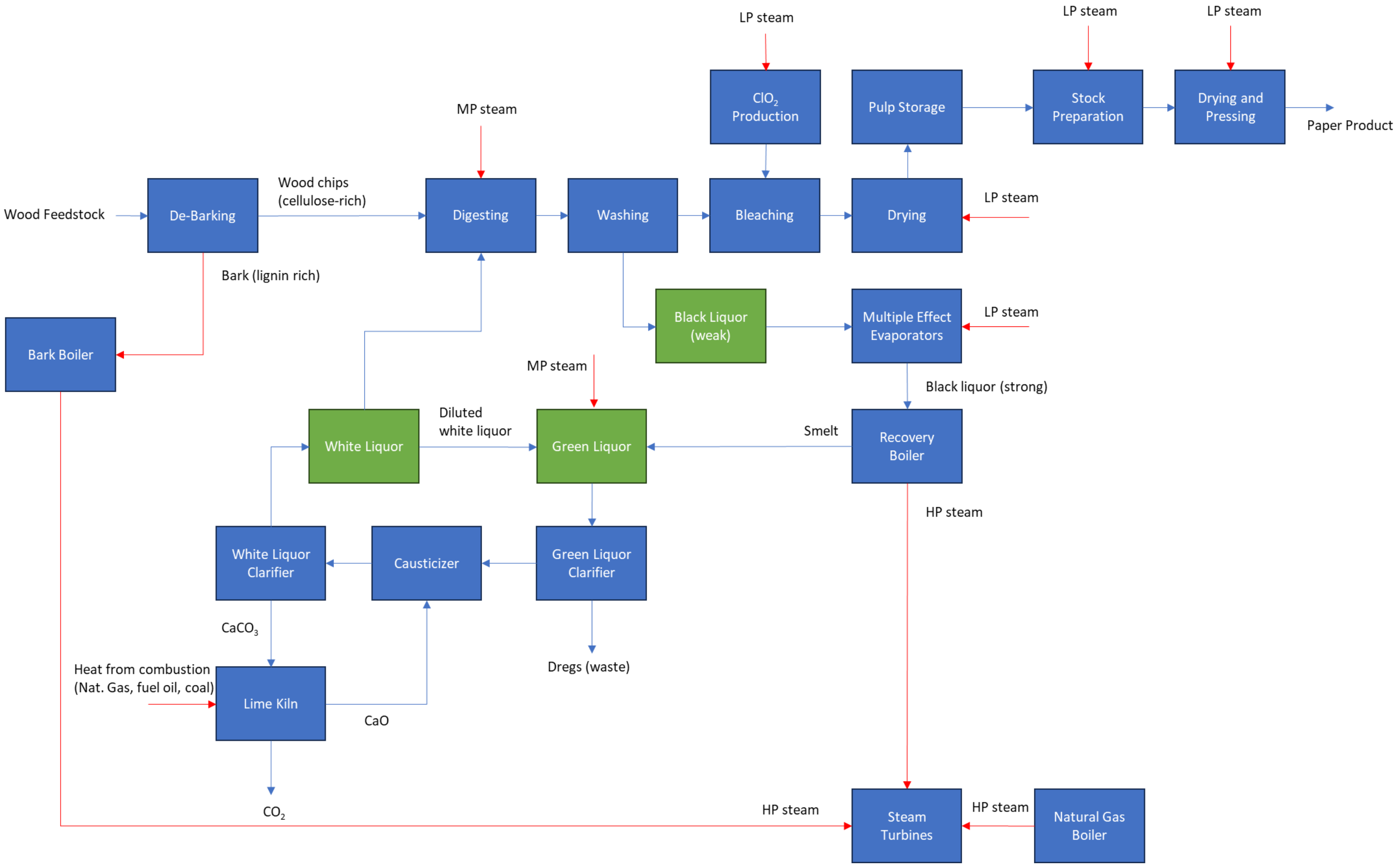
Kraft Cycle Block Diagram



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Reference Plant Summary

Specification	Value	Notes
Capacity	400,000 ADT/yr	Unbleached pulp and paperboard
Uptime	350 days/yr	
Wood Processed	2,554 mt/day	Oven Dried (OD) Softwood
Electricity Load	25 MWe	
Heat from Fuel Combustion	28 MWt	
Heat from Byproduct Combustion	185 MWt	
Steam Demand	156 MWt	
CO2 output	437,000 MT/yr biogenic 45,900 MT/yr non-biogenic	91% biogenic & 9% non-biogenic

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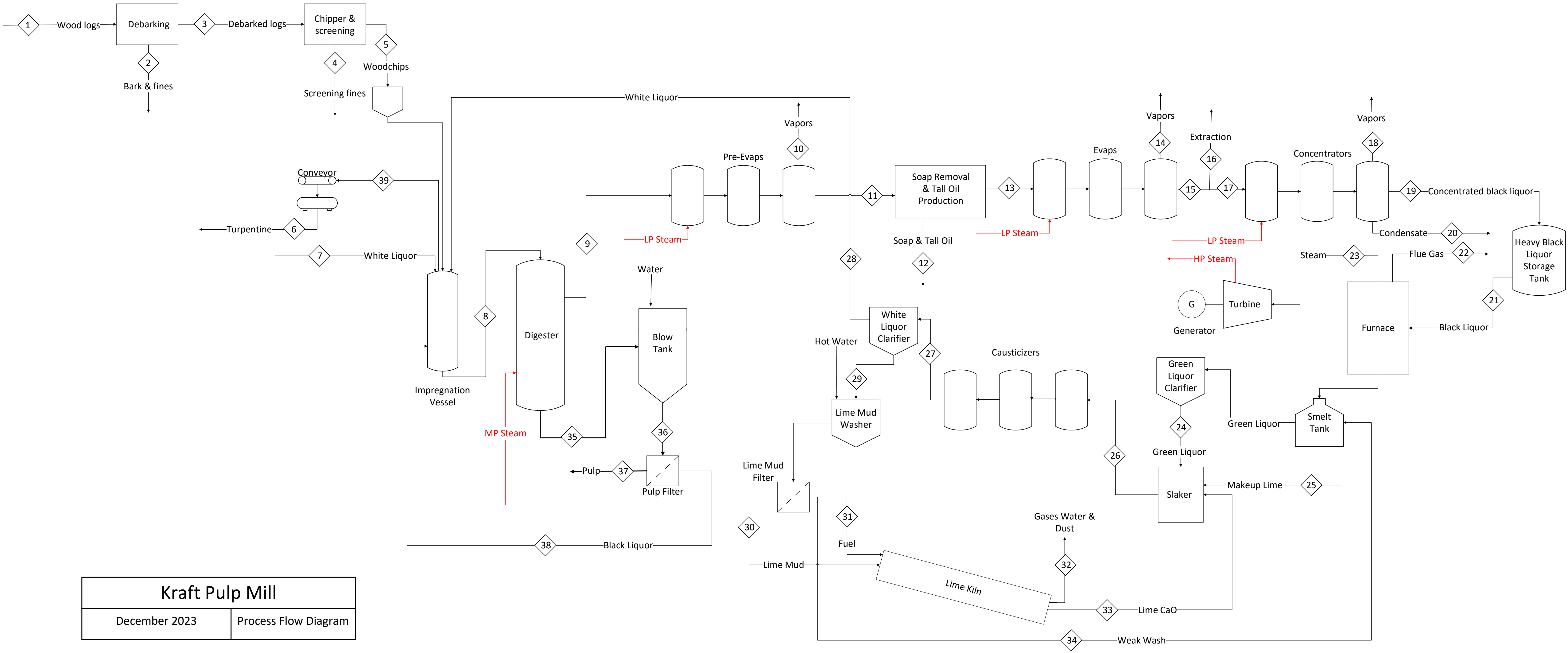
Kraft Pulp Mill and Chemical Recovery Process Flow Diagram



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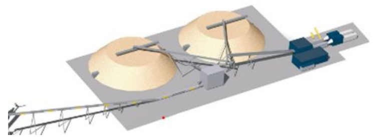
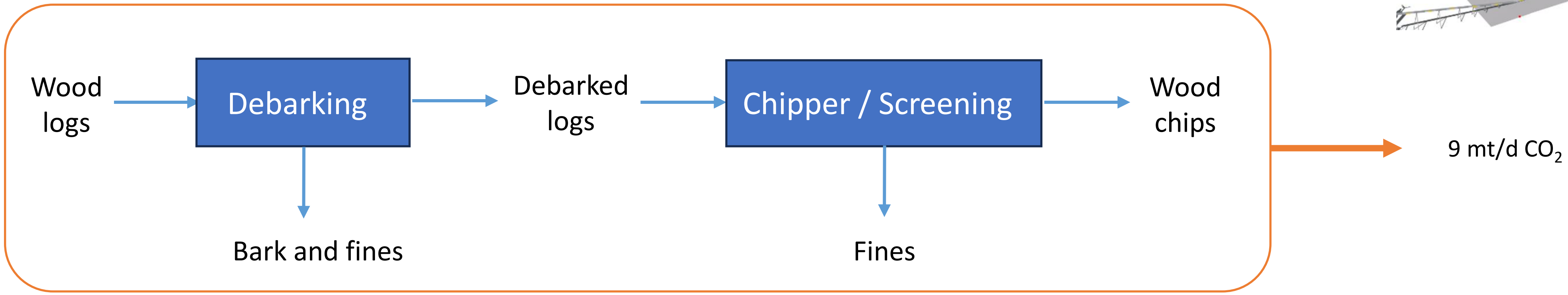
Wood Processing

Woodyard:





Assuming a reference kraft pulp mill capacity of 400,000 ADt/yr

Type of Process	Pulp mill
Pulp production ADt/year	**400,000**
Pulp production ODt/year (MC 7-10%)	360,000
Uptime days	350
OD Biomass (mt/Year)	893,971
OD Biomass (mt/d) day	2,554
Wet Biomass (mt/d)	4,819
Moisture (%)	47%
Water (mt)	2,265

Basis process: Softwood Kraft pulping:
Feedstock: Southern Pine, particularly Southern Yellow Pine and Longleaf Pine
Final product: Coniferous wood pulp

Woodyard	Mass losses
Bark+Fines	9.0%
Screening room	3.0%

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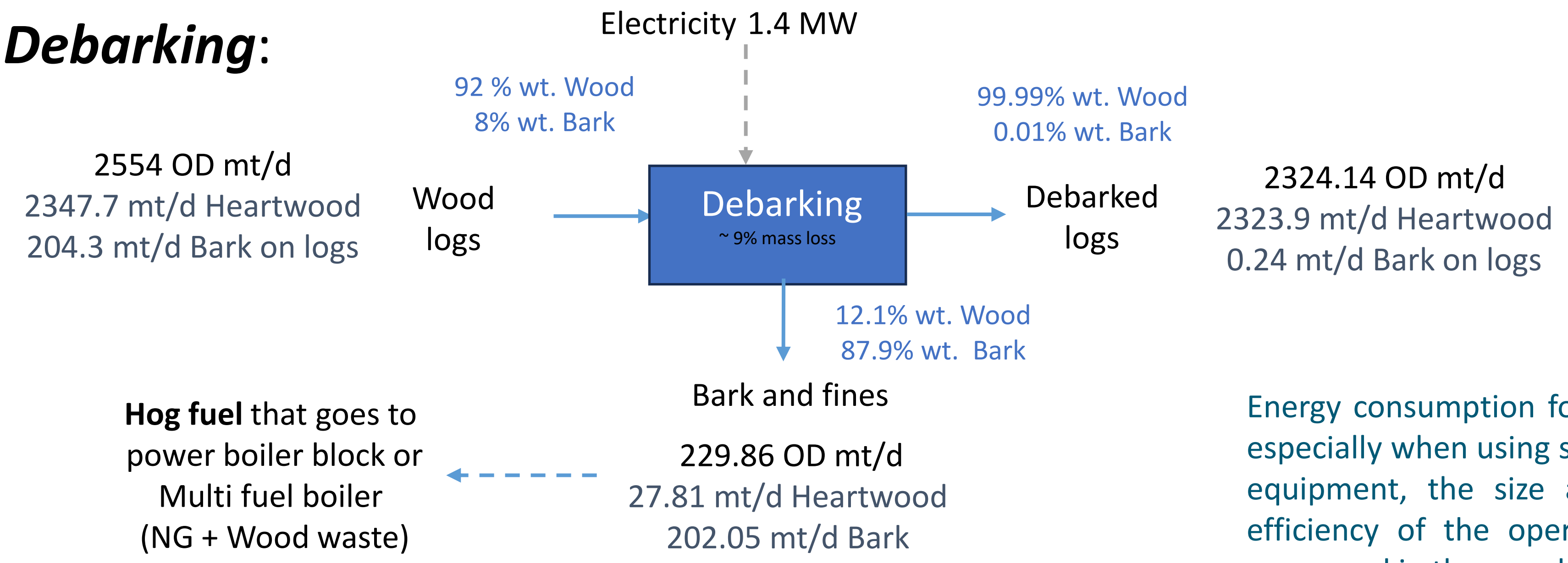
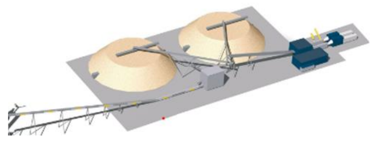
Wood Processing

Debarking:





Energy consumption for log debarking and chipping in P&P industry, especially when using softwoods, can vary based on type of debarking equipment, the size and moisture content of the logs, and the efficiency of the operation; for the reference plant 1.4 MW was consumed in the woodyard.

Here are some factors that can influence the energy consumption in logs debarking:

- ***Equipment Efficiency:*** Modern, well-maintained debarking machines tend to be more energy-efficient.
- ***Log Size and Moisture Content:*** Larger and drier logs may require less energy.
- ***Debarking Process:*** Different debarking methods (e.g., drum debarkers, ring debarkers, or flail debarkers) have different energy requirements.
- ***Wood Species:*** The specific softwood species being processed can influence energy consumption.
- ***Scale of Operations:*** Larger facilities may have more efficient processes and economies of scale, which reduce energy consumption per ton of debarked logs.
- ***Local Conditions:*** Environmental factors such as temperature and altitude can influence energy consumption.

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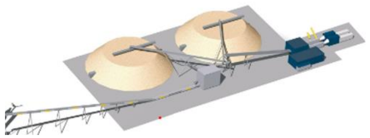
Wood Processing

Chipper and screening:



2324.14 OD mt/d
2323.9 mt/d Heartwood
0.24 mt/d Bark on logs

Debarked logs

99.99% wt. Wood
0.01% wt. Bark

Chipper & screening
~ 3% mass loss in sizing

99.99% wt. Wood
0.01% wt. Bark

Wood chips

2248 OD mt/d
(25-35 mm long, 25-35 mm wide and 4-10 mm thick)
2247.77 mt/d Heartwood
0.23 mt/d Bark on chips

Clean chips that go to digestion and sulfate turpentine recovery unit

99.99% wt. Wood
0.01% wt. Bark

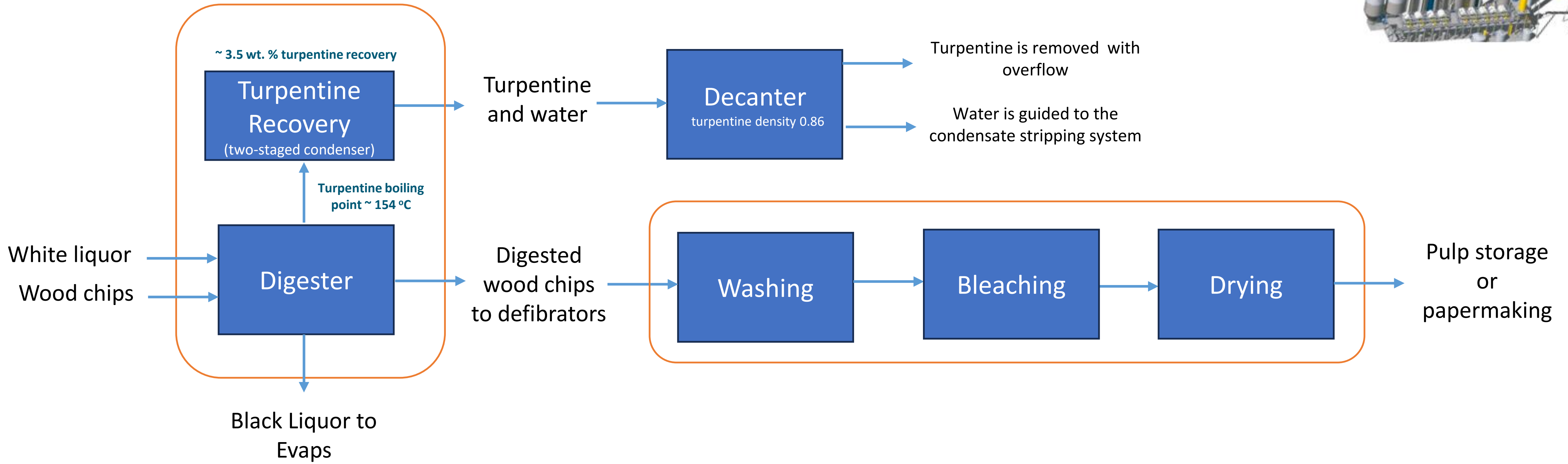
Screening room fines

76.14 OD mt/d
76.13 mt/d Heartwood
0.01 mt/d Bark

Several factors can influence the energy consumption in wood chipping:

- ***Equipment Efficiency:*** The type and condition of chipping equipment plays a significant role. Newest equipment is most energy-efficient.
- ***Wood Moisture Content:*** Drier wood requires less energy to chip compared to wet wood. Drying the wood before chipping can reduce energy consumption.
- ***Chipping Process:*** The specific chipping process used can impact energy consumption. The use of disk or drum chippers can have different energy requirements.
- ***Wood Species:*** Different softwood species can have variations in energy requirements for chipping.
- **Scale of Operations:** Larger facilities may have more efficient processes and economies of scale, which reduce energy consumption per ton of wood chips.
- ***Local Conditions:*** Environmental factors such as temperature and altitude can influence energy consumption.

Chemical Separation, Digesting and Washing



Digester	
Pulping Yield	46.41%
Kappa Number (1-115), residual lignin content	48.0
Pulp Production adt/day	1143
Pulp production Odt/day	1039
Top gas phase Temp C	161

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Chemical Separation – Turpentine Recovery During Digestion

Turpentine recovery:

2248 OD mt/d
(25-35 mm long, 25-35 mm wide and 4-10 mm thick)
2247.77 mt/d Heartwood
0.23 mt/d Bark on chips

99.99% wt. Wood
0.01% wt. Bark

Wood Chips System Load → **Turpentine Recovery** (~ 3.5 % turpentine recovery) → Wood Chips

100% wt. Wood

2240 mt/d
2247 mt/d Heartwood

Effective wood chips that undergoes digestion

85% wt. Turpentine
15 % wt. water

Turpentine
(Boiling point 154 ± 4 °C)

8 mt/d
7 mt/d Turpentine
1 mt/d H2O

To decanter for further separation

Crude turpentine or pinene can be recovered from certain coniferous pulp woods, particularly southern yellow pine and longleaf pine, during the cooking period of a wood charge in digesters. The extent of turpentine recovery in gallons per ton of pulp produced, depends on the type, age and origin of the wood.

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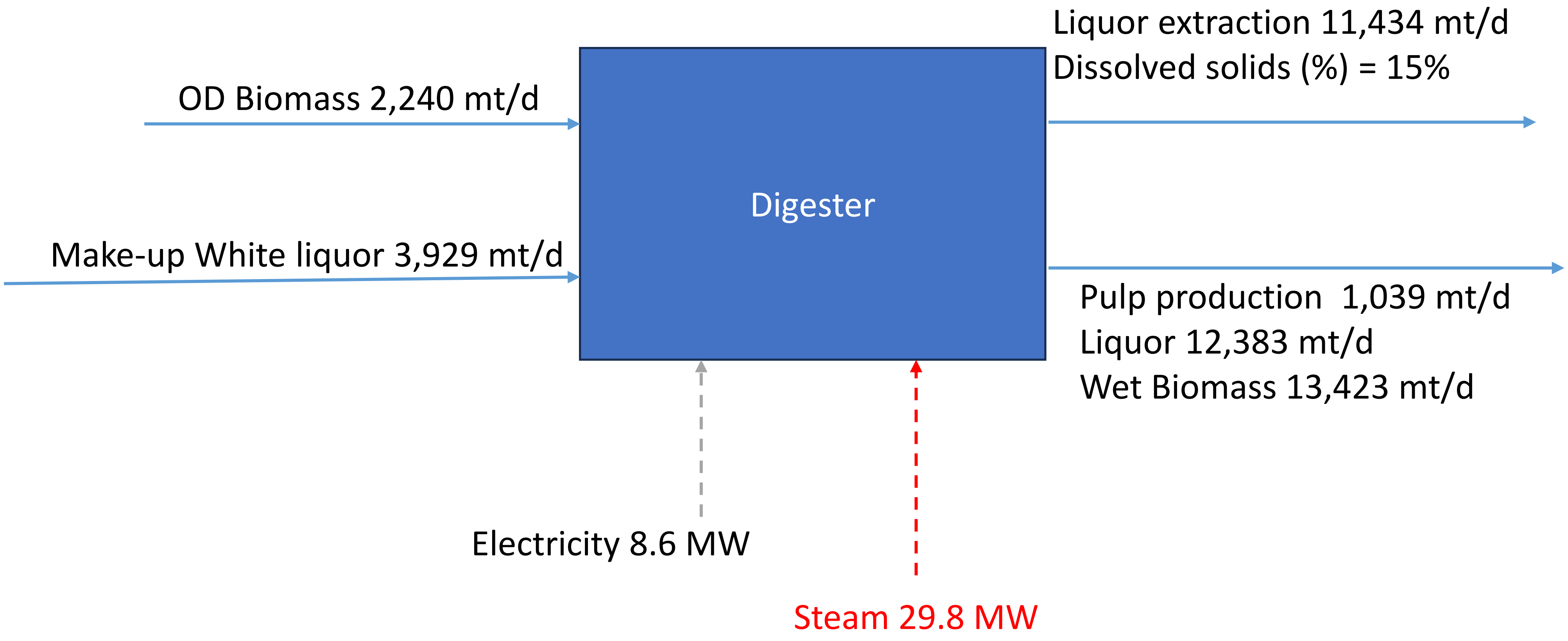
Digester

Pulping section:



- For kraft pulping, the steam consumption can range from about ***1.2-2.5 metric tons of steam per metric ton of pulp (MT steam/MT pulp).***
- ***Kappa number (residual lignin) = 48.0***

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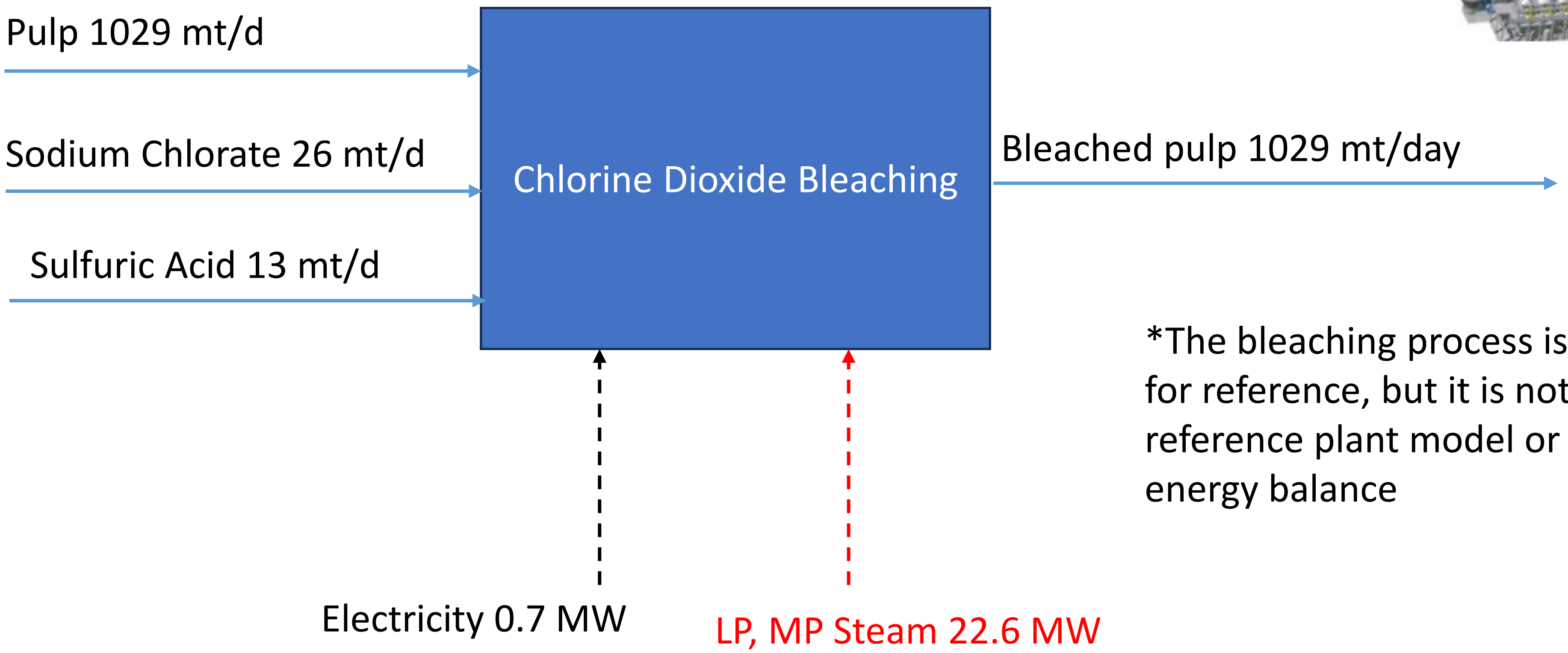
Bleaching Stage*



*The bleaching process is included here for reference, but it is not included in the reference plant model or in the overall energy balance

[ACEEE Energy Balance for Kraft Pulp Mill]

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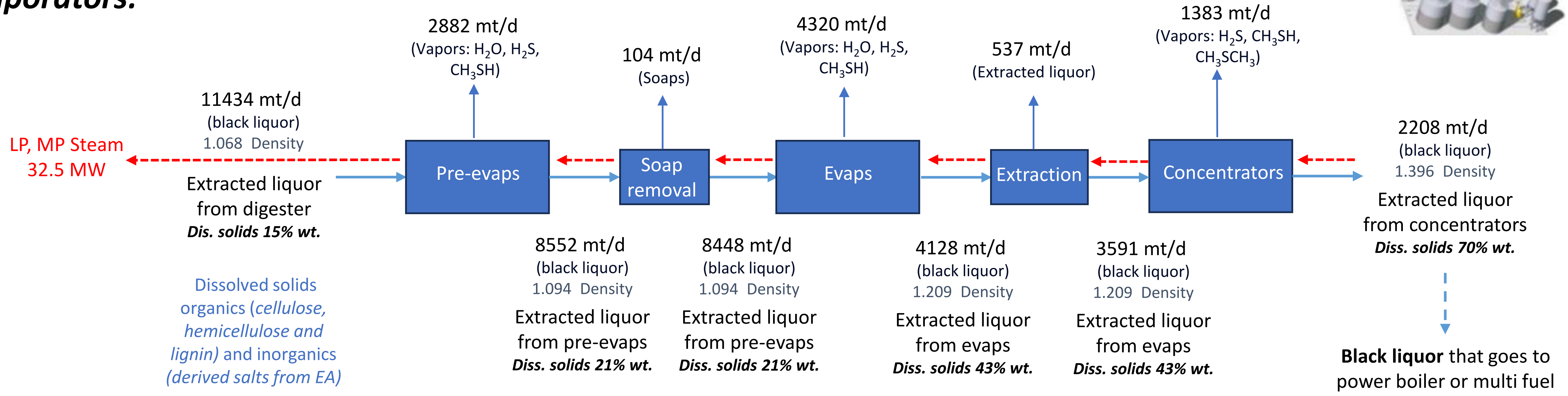
Evaporation

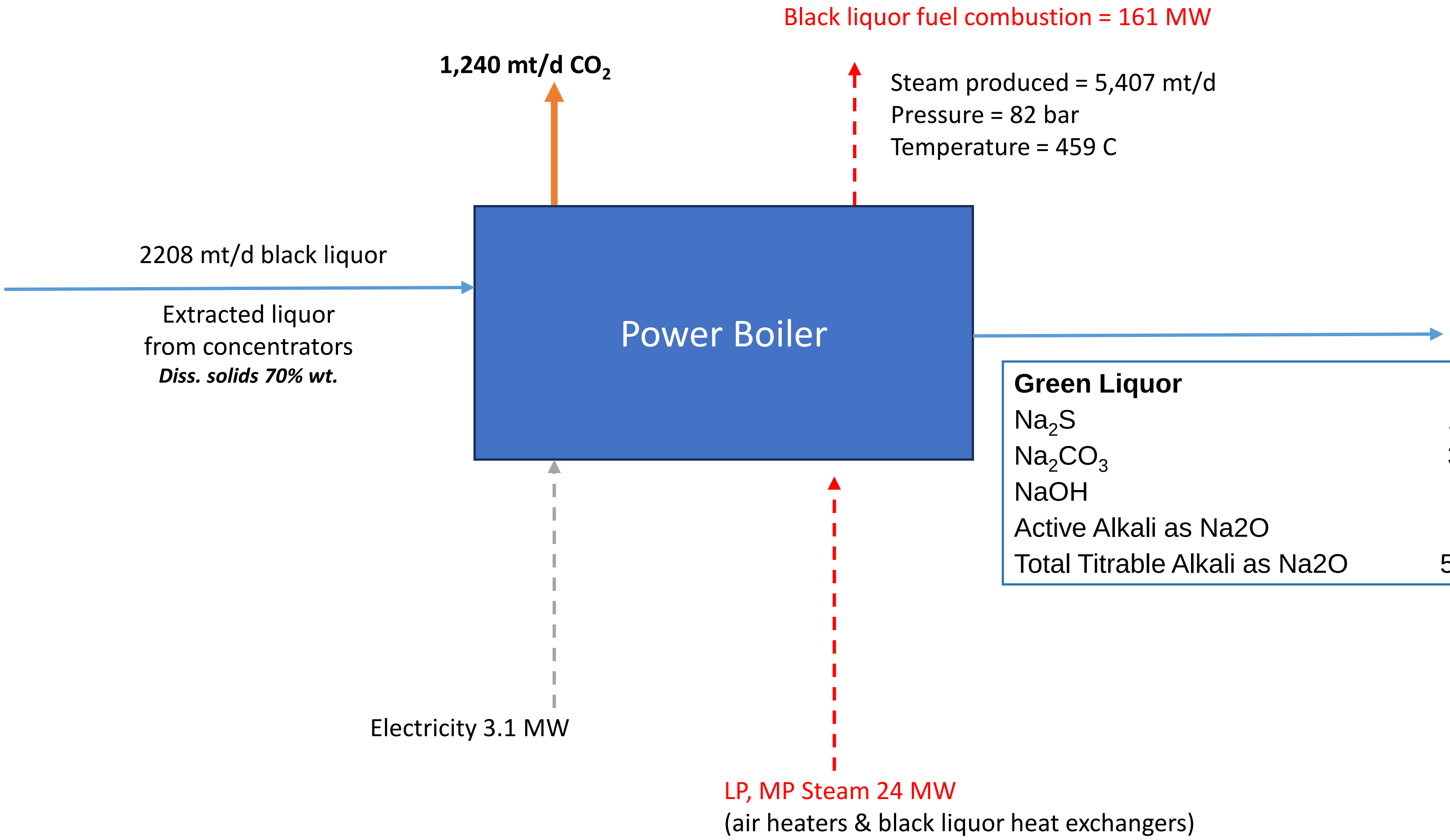
Evaporators:



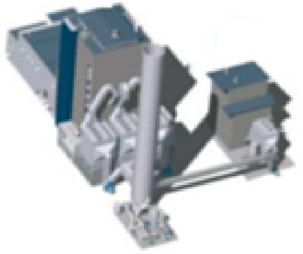
Commonly, multiple effect evaporators are more energy-efficient, as it uses the latent heat of steam to evaporate water from the black liquor in multiple stages. Around 1204 tons of steam a day are used in the evaporation plant.

The black liquor is an aqueous solution of lignin residues, hemicellulose, and inorganics chemicals used in the cooking process. It comprises 15% solids by weight of which two-thirds are organic chemicals and the remainder are inorganic. Normally the organics in black liquor are 40–45% soaps, 35–45% lignin and 10–15% other organics.

Black Liquor to Power Boiler



Green Liquor	
Na_2S	101 mt/d
Na_2CO_3	365 mt/d
NaOH	62 mt/d
Active Alkali as Na2O	164 mt/d
Total Titrable Alkali as Na2O	529 mt/d



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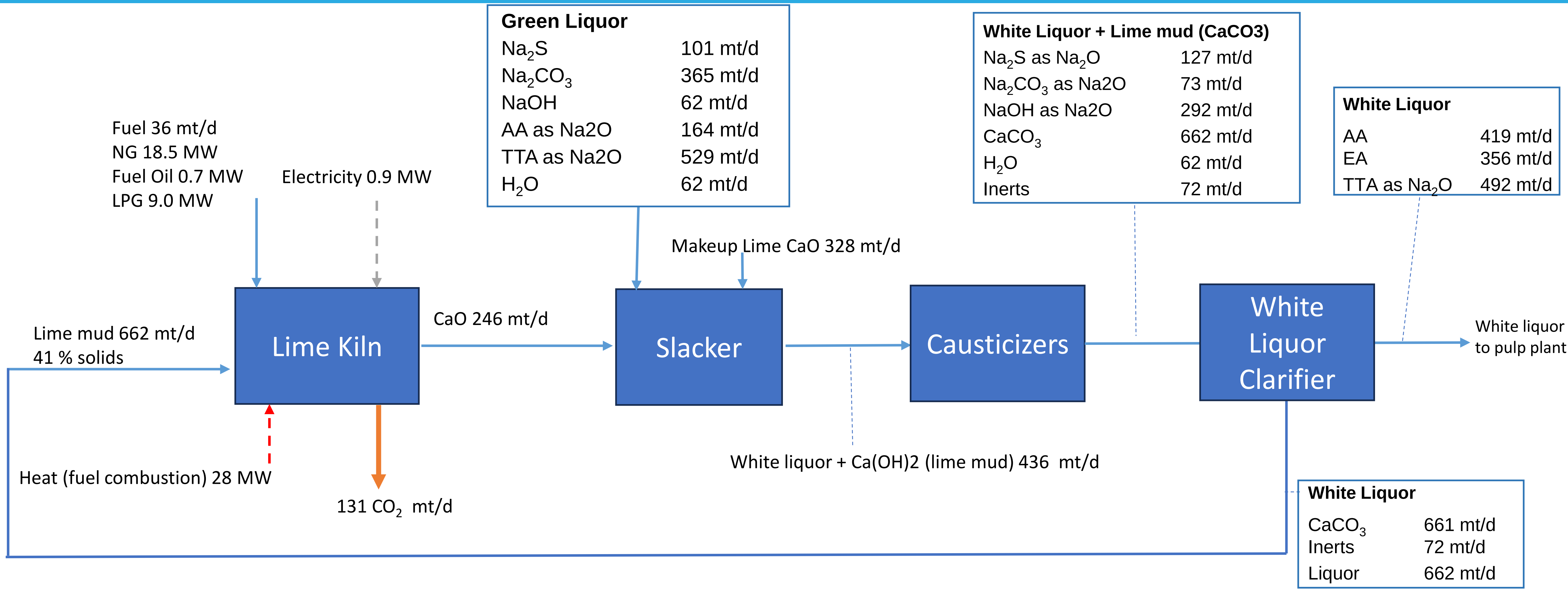
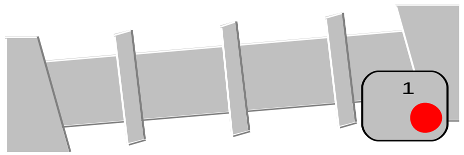
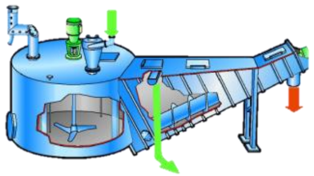
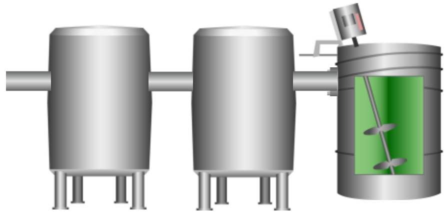
Calcination and Recausticizing









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Overall Energy Requirements

Overall Energy & Chemical Requirements												
PO #	Process Unit	Electricty Demand	Heat Demand from Fuel Combustion	Steam Demand	Steam Quality	Byproduct Fuel Source	Heat of Combustion of Byproducts (LHV)	Sodium Hydroxide	Sodium Sulfide	Sodium Chlorate	Sulfuric Acid	Calcium Oxide
		MWe	MWt	MWt			MWt	kg/d	kg/d	kg/d	kg/d	kg/d
A	Wood Processing	1.4										
B	Hog Fuel Boiler *	2.0				bark & fines	23.8					
C	Pulp Plant	8.6		29.8	LP, MP			73,000	292,000			
D	Bleaching*	0.7		22.6	LP, MP					25,915	12,958	
E	Pulp Drying*	5.2		47.4	LP							
F	Evaporation Plant	1.4		32.5	LP, MP							
G	Lime Kiln + Causticizing	0.9	28.1									83,970
H	Recovery Boiler	3.1		24.1	LP, MP, HP	black liquor solids	161.0					
I	Wastewater Plant*	2.0										
	Total	**25**	**28**	**156**			**185**					

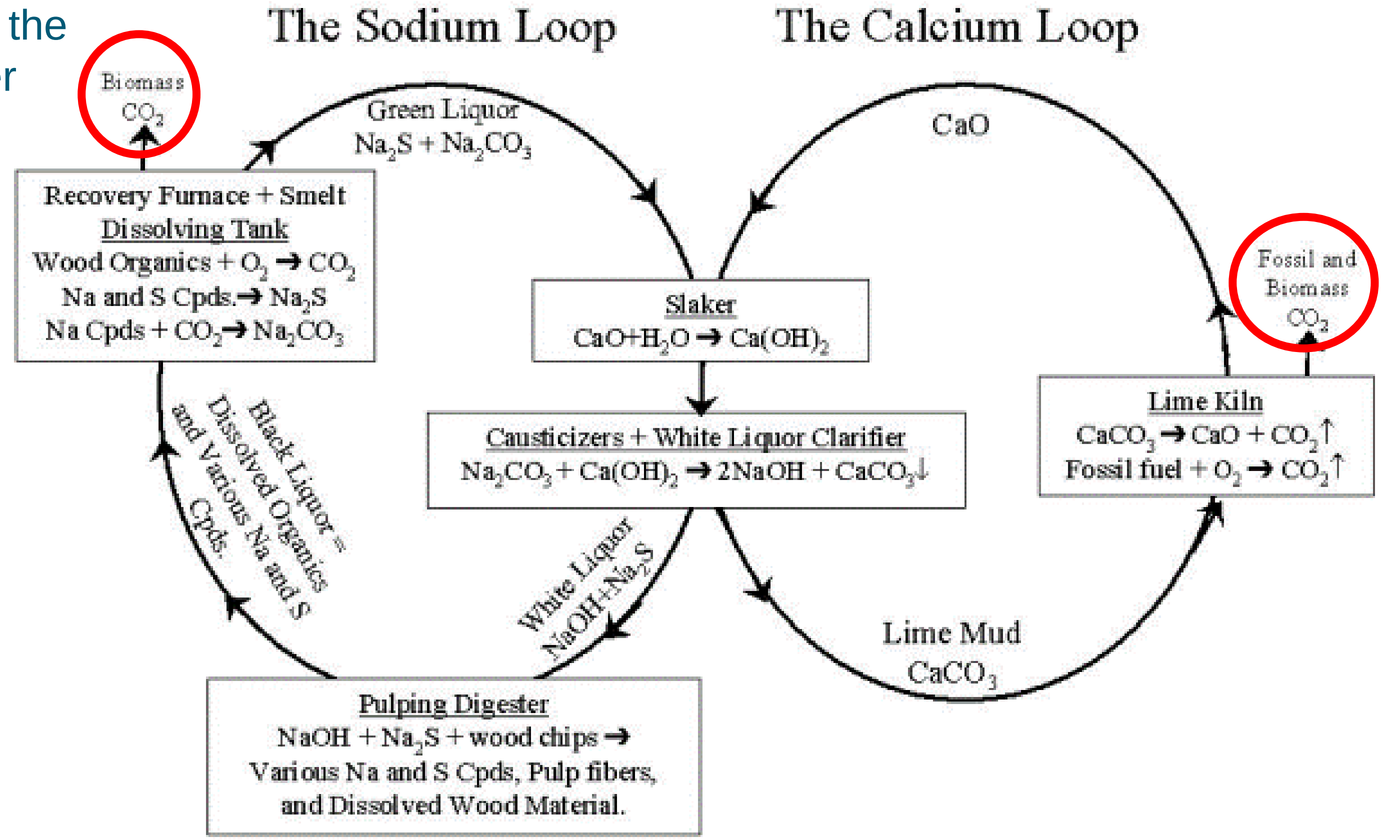
*electricity and steam demands are calculated using ACEEE data

(Orr 1995)

CO_2 Emissions: Reference Mill Estimation and Nationwide Comparison

CO2 Emissions

~ 90-85 % of total emissions are generated in the recovery boiler



~ 10-15 % of total emissions are produced in chemical recovery plant section

1 ton CO_2 emitted per ton lime (CaO) produced

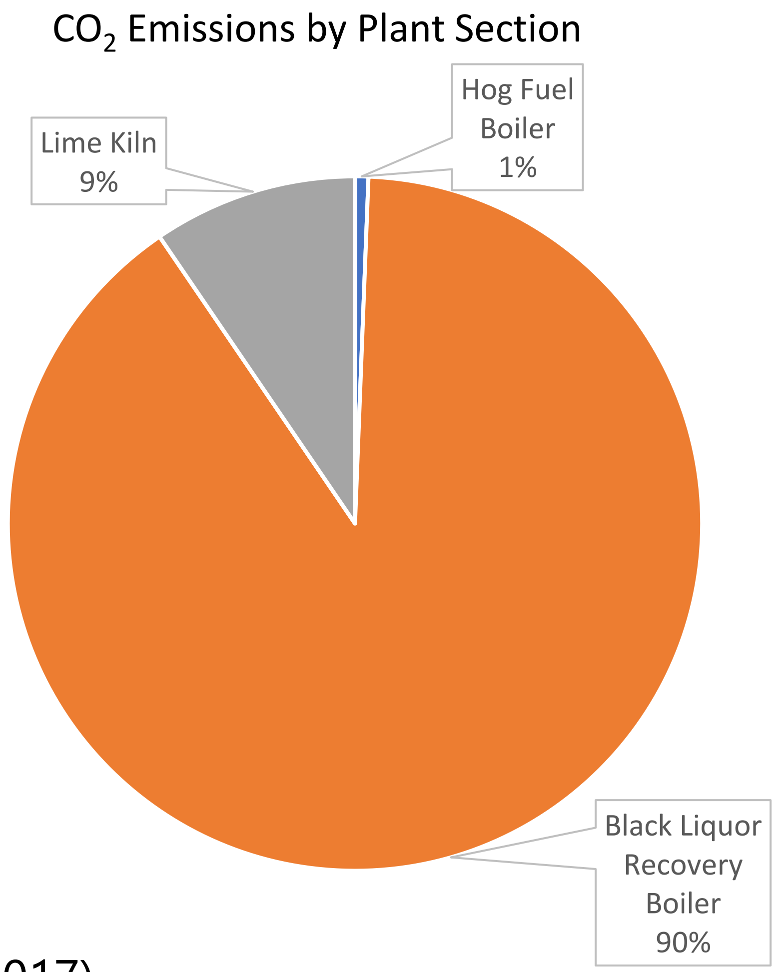
(Yang et al. 2021)

EPA 2009

CO2 Emissions Continued

- **Hog fuel reboiler emissions:**
  - Bark + Fines = 300 mt/day
  - Byproduct fuel combustion= 24 MW
  - Assuming an emission factor of 15 kg CO_2/MWh
  - CO2 emissions from combustion of wood chips = **3,000 mt/yr**
- **Recovery boiler emissions:**
  - Black liquor feed = 1500 mt/d
  - Byproduct fuel combustion = 161 MW
  - Assuming an LHV of 9 MJ/kg for black liquor solids
  - 321 kg CO2 per MWh black liquor solids
  - CO2 emissions from combustion = **434,000 mt CO2/yr**
- **Lime kiln emissions:**

Fuel Type	Metric Ton CO2/year
Natural Gas	28,000
Fuel Oil	1,500
LPG	16,400
Total	45,900



(Vakkilainen 2017)
(Hanks and Gooden 2013)
(NCASI 2005)

Reference Plant and National Scale CO_2 Emissions

PO #	Process Unit	Average Plant CO2 Emissions	National Scale CO2 Emissions
		MT/yr	MMT/yr
A	Wood processing		
B	Hog Fuel Boiler	3,000	20.3
C	Pulp Plant		
D	Bleaching		
E	Pulp Drying		
F	Evaporation Plant		
G	Lime Kiln + Causticizing	45,900	18.9
H	Recovery Boiler	434,000	57.4
I	Wastewater plant		
	Total	**482,900**	**96.6**

(EPA n.d.)
(EPA 2022)

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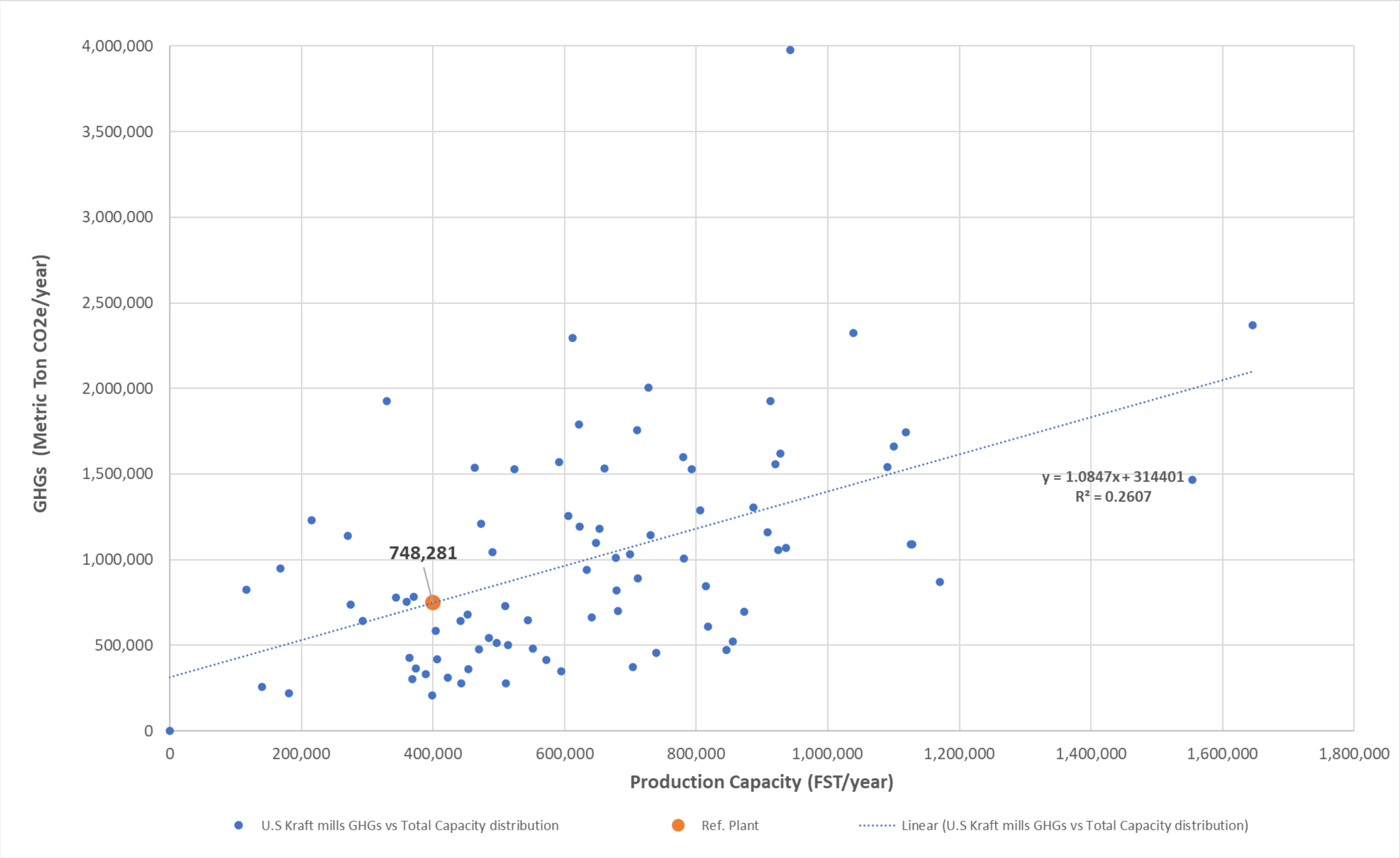
Reference Kraft Mill Emissions Estimation



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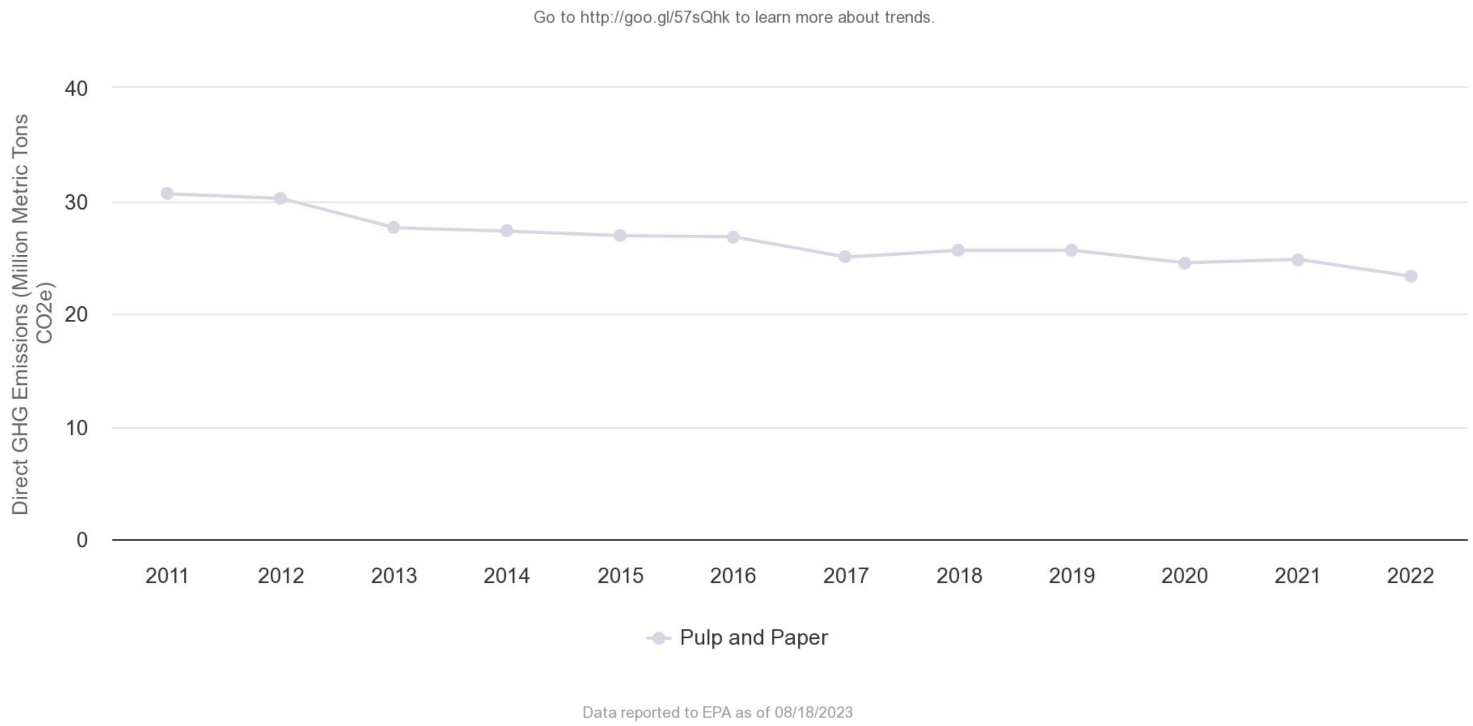
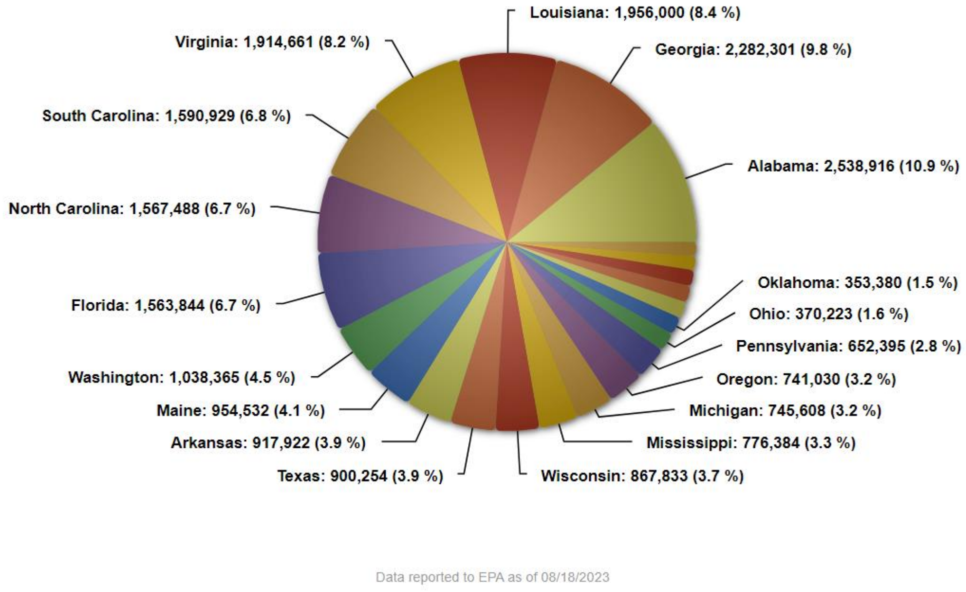
Direct GHGs Emissions (CO2, CH4 and Fluorinated)

U.S. - Direct GHG Emissions Reported by Sector in Million Metric Tons of CO2e (2011-2022)





14.3 Million Metric tons CO2 eq (60%) produced in Southeast
13.7 Million Metric tons CO2 eq (95% of total GHGs) is CO2

A total of 23 Million Metric tons CO2 eq produced in the U.S

(U.S. EPA Office of Atmospheric Protection 2023)

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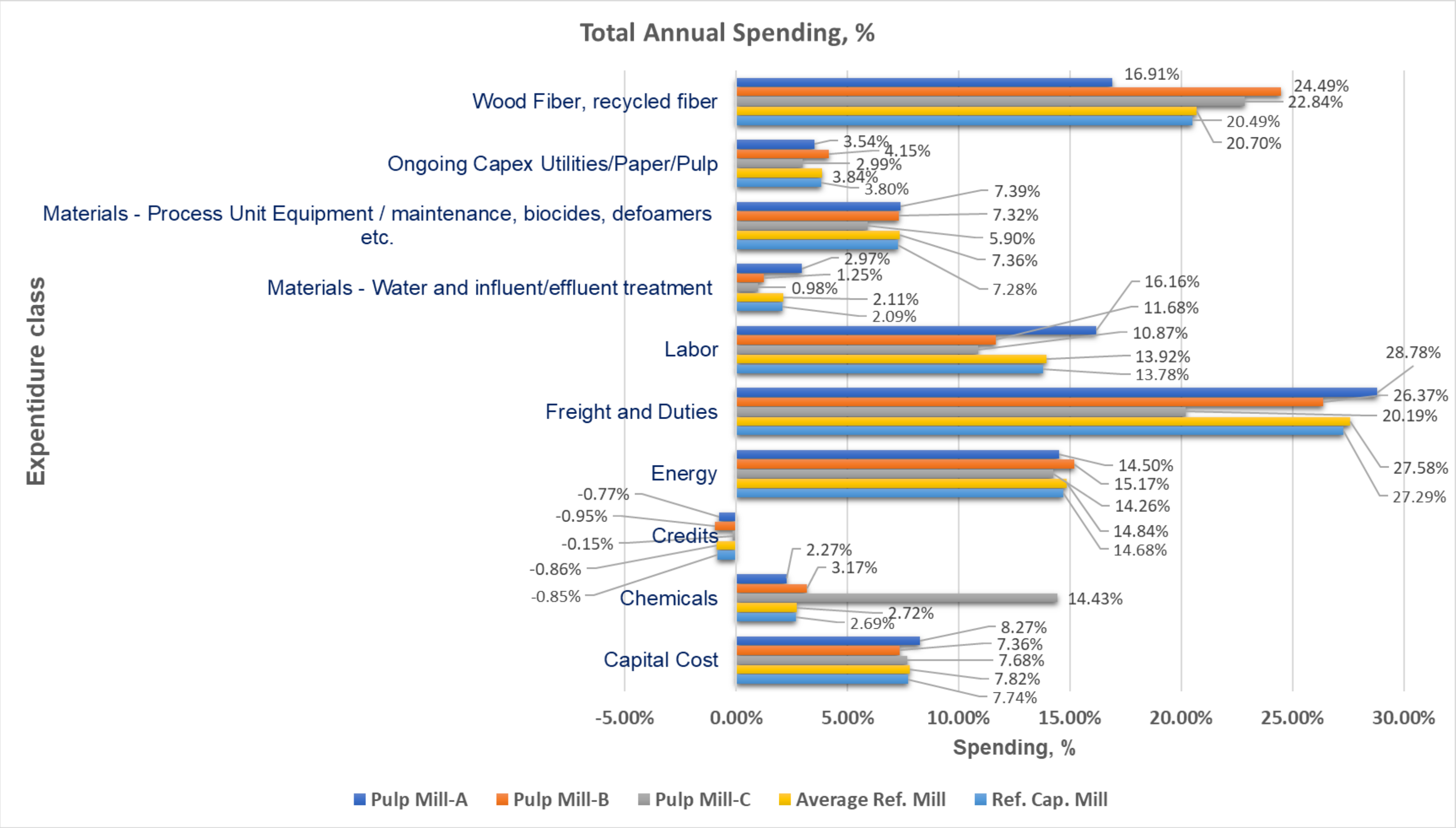
Operating Costs

Operating Costs Estimations

Mill	*Pulp Mill-A*	*Pulp Mill-B*	*Pulp Mill-C*	*Average Mill*	*Ref. Cap. Mill*
Type of Kraft Pulp Mill	Virgin and recycled integrated	Virgin and recycled integrated	Virgin integrated	Virgin and recycled integrated	Virgin and recycled integrated
Type of pulp	Unbleached pulp	Unbleached pulp	Bleached pulp	Unbleached pulp	Unbleached pulp
Capacity ADT (FST)/yr	**453,250**	**399,170**	**359,970**	**404,130**	**400,000**
Spending	**Total Annual Spending, USD**				
Capital Cost	19,577,830	16,564,877	24,782,882	18,071,354	17,886,674
Chemicals	5,794,303	7,120,100	46,496,446	6,457,202	6,391,212
Credits	-2,345,419	-2,133,762	-494,982	-2,239,591	-2,216,703
Energy	40,040,680	34,088,636	45,886,853	37,064,658	36,685,876
Freight and Duties	74,738,834	59,238,102	64,983,179	66,988,468	66,303,880
Labor	41,561,471	26,230,660	34,972,067	33,896,066	33,549,665
Materials - Water and influent/effluent treatment	8,712,595	2,833,509	3,147,146	5,773,052	5,714,054
Materials - Process Unit Equipment / maintenance, biocides, defoamers etc.	19,157,099	16,476,947	18,984,520	17,817,023	17,634,942
Ongoing Capex Utilities/Paper/Pulp	9,552,162	9,306,292	9,630,392	9,429,227	9,332,865
Wood Fiber, recycled fiber	45,393,559	55,025,261	73,510,973	50,209,410	49,696,296
Total	***262,183,114***	***224,750,622***	***321,899,476***	***243,466,868***	***240,978,762***
Unit Annual Cost (per FST/yr)	***$578***	***$563***	***$894***	***$602***	***$602***

(Fisher International 2023)

Operating Cost Estimations

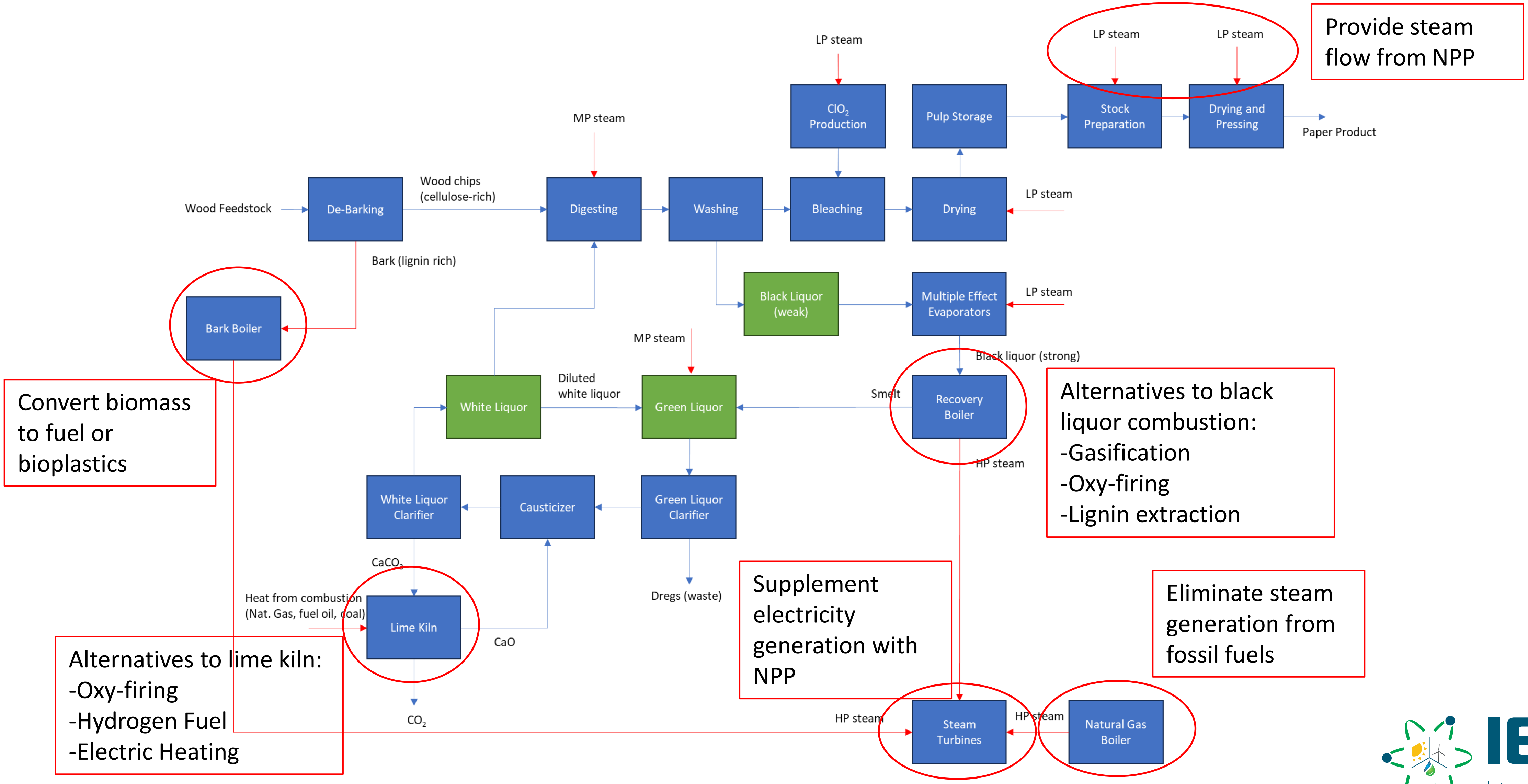


Mill	Pulp Mill-A	Pulp Mill-B	Pulp Mill-C
Type of Kraft Pulp Mill	Virgin and recycled integrated	Virgin and recycled integrated	Virgin integrated
Type of pulp	Unbleached pulp	Unbleached pulp	Bleached pulp

(Fisher International 2023)

Nuclear Integration Opportunities

Decarbonization Opportunities



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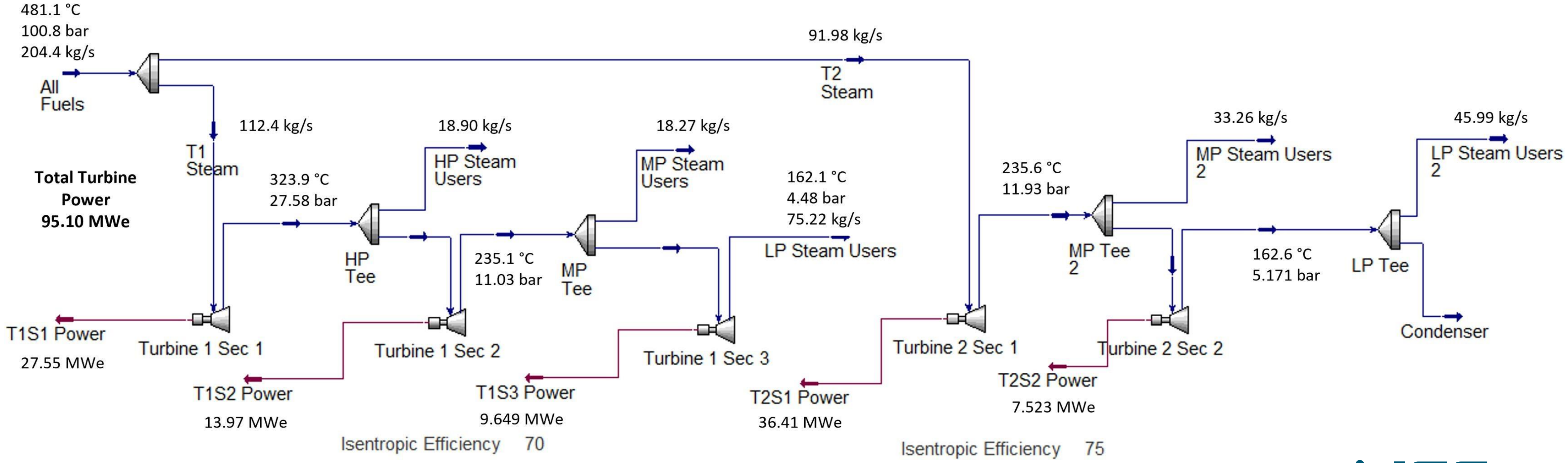
Provide steam and electricity with NPP

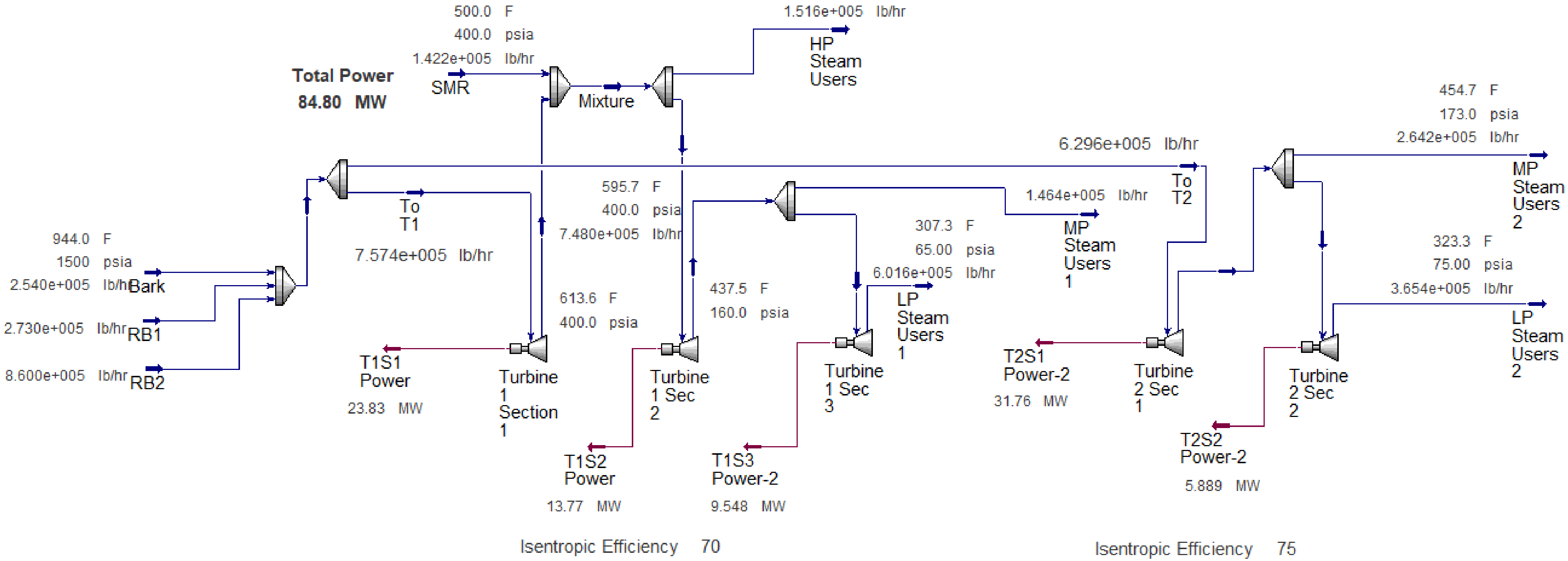
- Paper mill steam and power plant without NPP integration



(Worsham and Terry 2022)

Provide Steam and Electricity with NPP

- Paper mill steam and power plant with NPP Integration (NuScale Design)



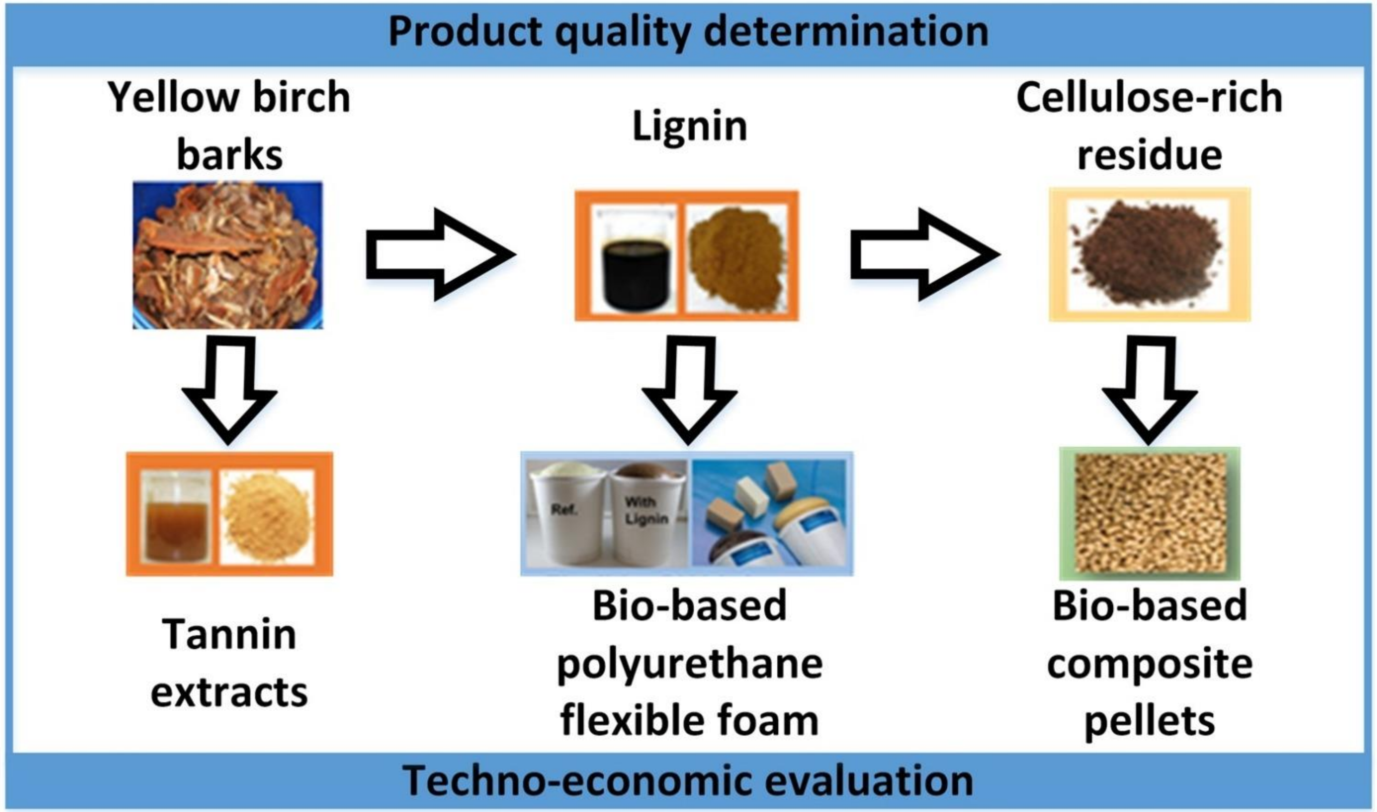
(Worsham and Terry 2022)

Nuclear Power Plant Options

- Low-temperature reactor
  - Provide steam and electricity
  - Provide MP or LP steam at outlet conditions, or use heat topping to obtain HP steam conditions
  - The majority of steam loads (evaporator and paper-making) can be met by outlet conditions
- High-temperature reactor
  - Provide steam and electricity
  - HP steam can be provided at outlet conditions
  - Utilize mill's on-site power plant to generate electricity through turbines and meet MP and LP steam conditions

Bark and Wood Fines

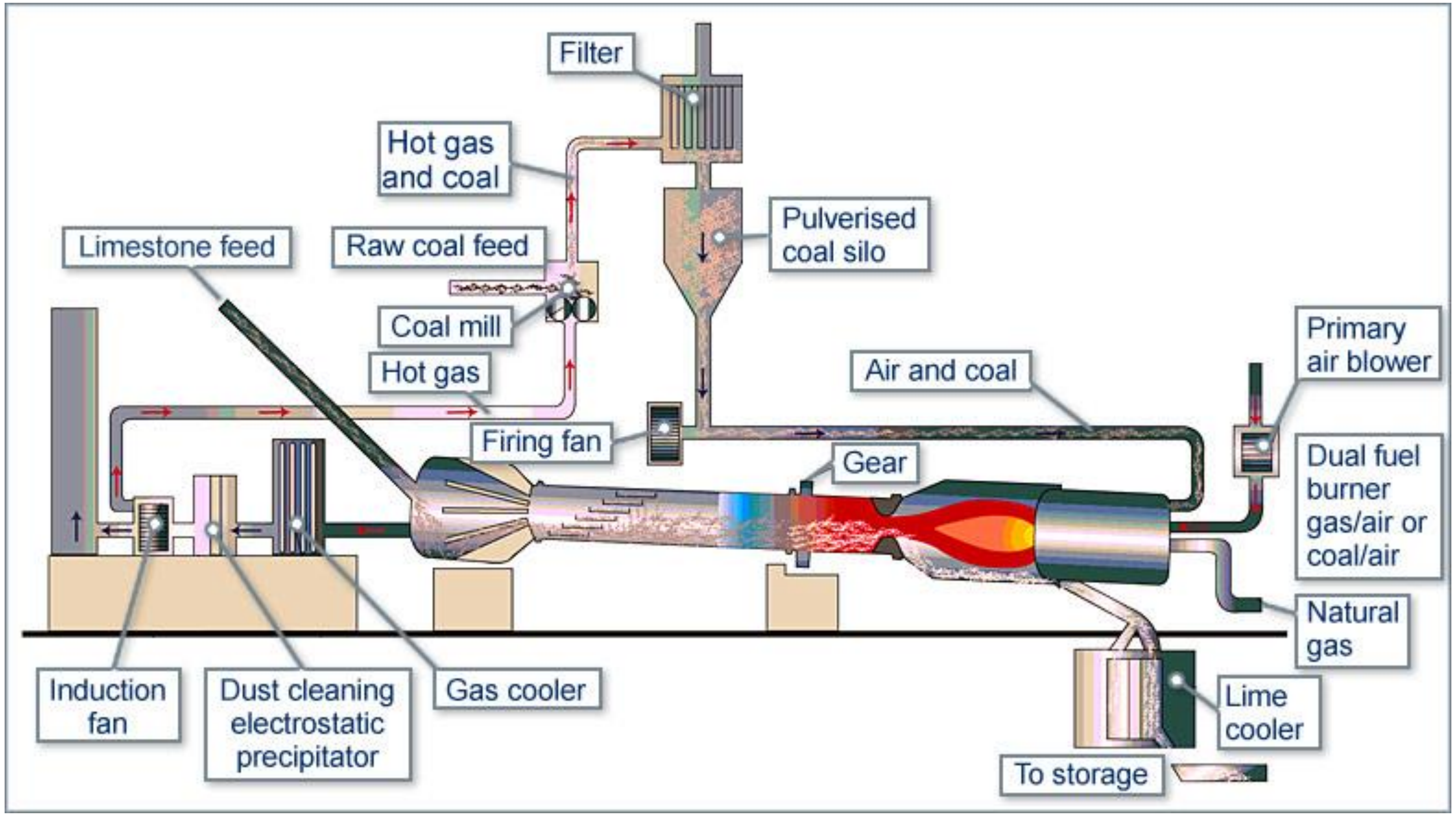
- With steam supplied from the NPP, wood waste can be diverted to bioproduct pathways.



(Olumoye et al. 2021)

Lime Kiln

- ~1 ton CO_2 is released for every ton lime produced, excluding the burning of fuel
- Nuclear heat cannot supply the high temperatures needed for the kiln (1000+ °C)
- New opportunities:
  - Electric heating
  - Oxy-fired combustion
  - Hydrogen as fuel



(European Lime Association 2023)

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Black Liquor Recovery Boiler

- ~1 ton CO_2 is released for every ton lime produced, excluding the burning of fuel
- Nuclear heat cannot supply the high temperatures needed for the kiln (1000+ °C)
- New opportunities:
  - Electric heating
  - Oxy-fired combustion
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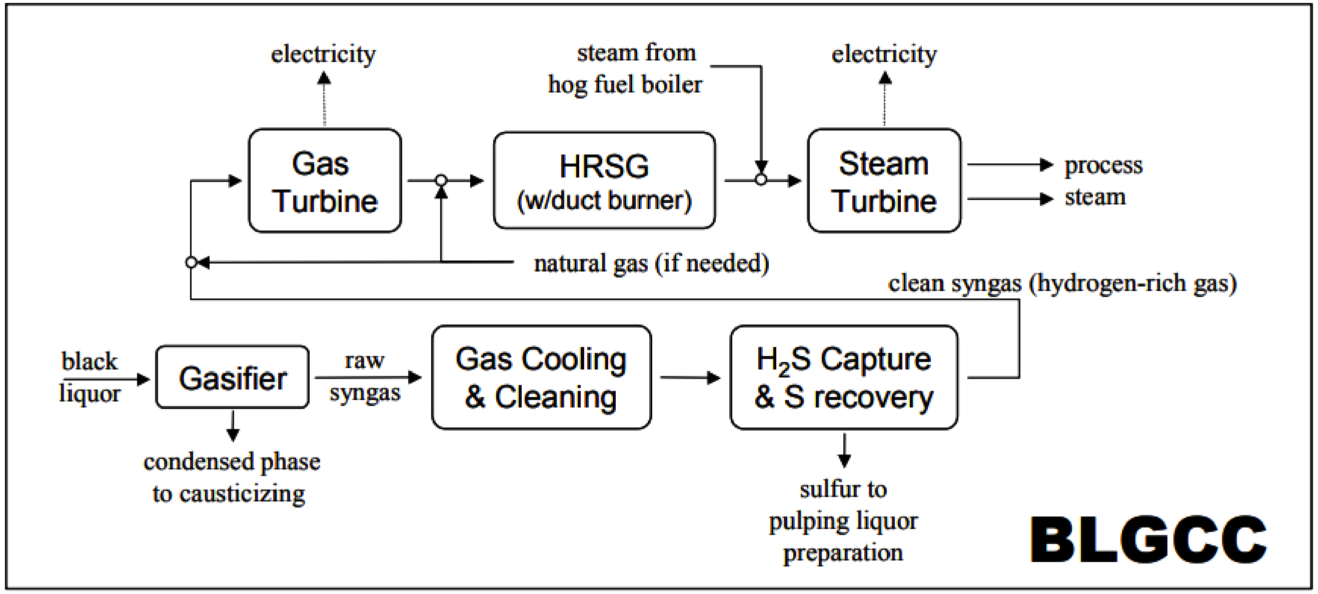

(Larson et al 2003)

Black Liquor Recovery Boiler

- Oxy-fired combustion can be employed to facilitate CO_2 capture
- Impacts to the chemical recovery process will need to be assessed

- Combustion
  - Fuel + O_2 + N_2 → CO_2 + N_2 + H_2O
- Oxy-Fuel Combustion
  - Fuel + O_2 → CO_2 + H_2O

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Hydrogen Opportunities

- Lime Kiln as a target for decarbonization
  - Small percentage (~10%) of total carbon emissions
  - Nearly all the fossil fuel usage at the reference mill
  - Arguably the easiest target at a Kraft Mill
  - E.g., most significant impact for smallest modification of the plant
- Blending pink H_2 into lime kiln natural gas supply
  - Up to 30 vol% to minimize retrofitting
  - Reference mill would require 61 kg/hr, demanding 2.1 MWe DC and 0.4 MWth of low-pressure steam for high-temperature steam electrolysis
  - Could eliminate 3,300 tons/year of fossil CO_2 (-10.9%)
  - Hydrogen could be evolved on-site or imported

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Future Work

Goals

30 days lookahead

- **Completed** generic plant design for P&P industry in the U.S. including all mass and energy balances, operating cost and rate of pollutants/emissions (M4 due 12/15/2023)
- Study Oxy-fire preliminary approaches for Lime Kiln and Recovery Boilers (M4 due 05/30/2024)
- Finalize Contract with North Carolina State University

60 days lookahead

- Begin collaboration with academia partner
- Make progress in the other kraft pulping process blocks modeling (~ Mid-end Jan)
- Built Preliminary models for Oxy-firing (~Feb)

90 days lookahead

- Complete the remaining kraft pulping processes modeling. Towards (M2 09/30/2024)
- Make progress in Oxy-firing modeling for Lime Kiln and Recovery Boilers including CO2 capture for chemicals production (M4 due 05/30/2024)

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