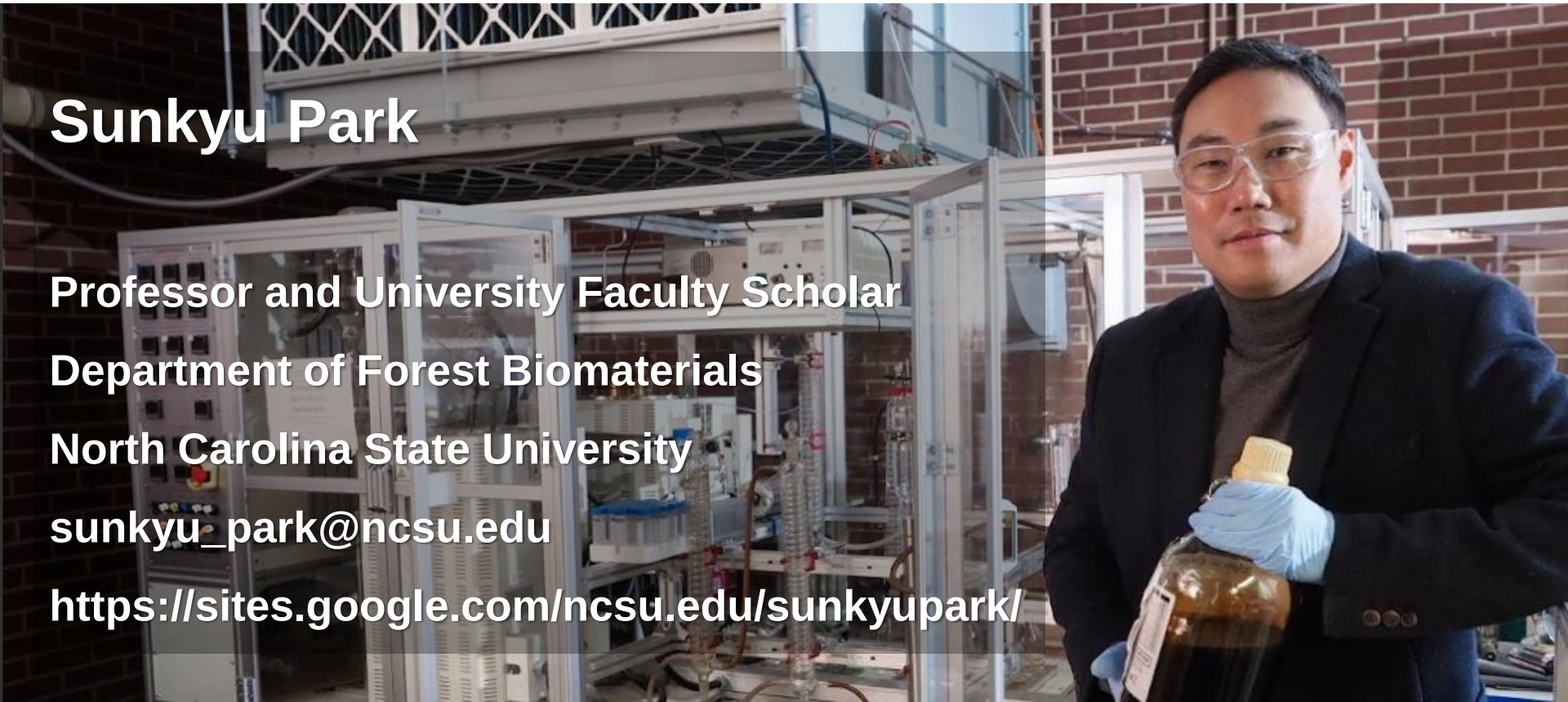
Decarbonization Challenges and Priorities in Forest Products Industry
DOE-EERE-IEDO, September 12, 2023, Atlanta, GA

Technical Challenges to Reduce Energy Use in Pulping and Chemical Recovery



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Acknowledgements

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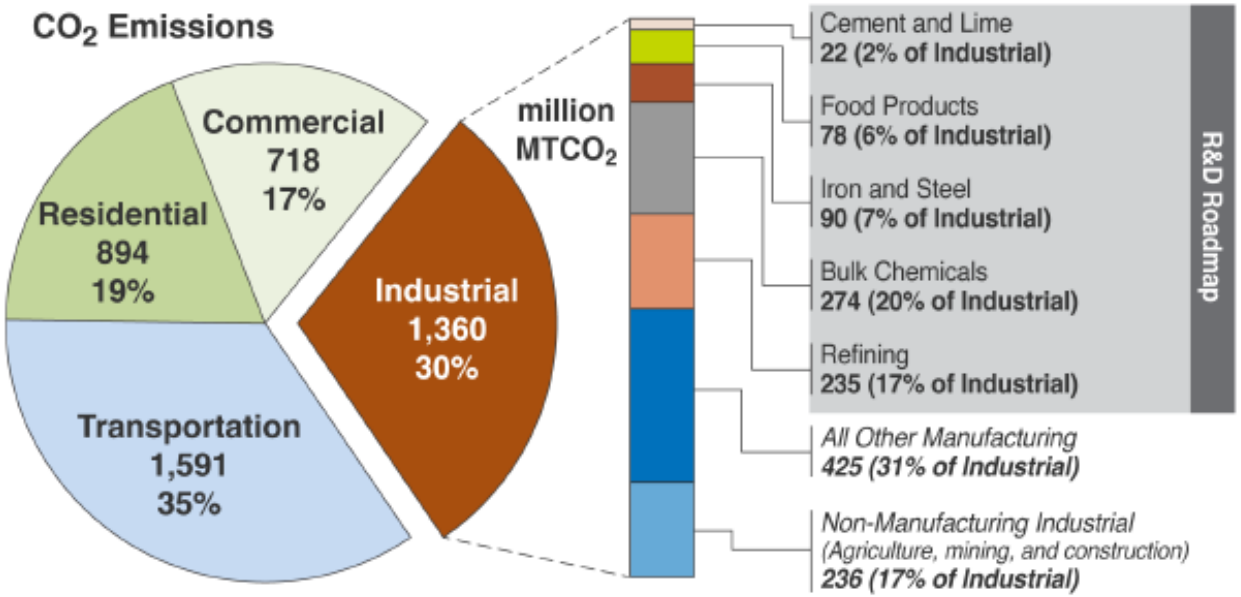
CO_2 Emission from Pulp and Paper Industry in US



DOE Industrial Decarbonization Roadmap, 2022

Based on our analysis, P&P emits ~150 million metric tons of CO_2 annually and ~77% CO_2 is biogenic

Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

ANALYSIS

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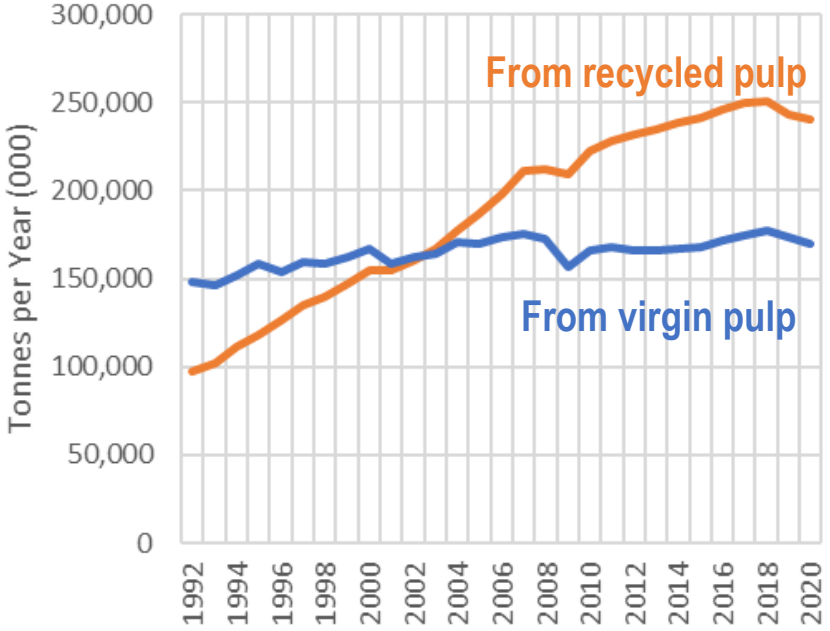
Cite this: DOI: 10.1039/d0ee01107j

Prospects for bioenergy with carbon capture & storage (BECCS) in the United States pulp and paper industry†

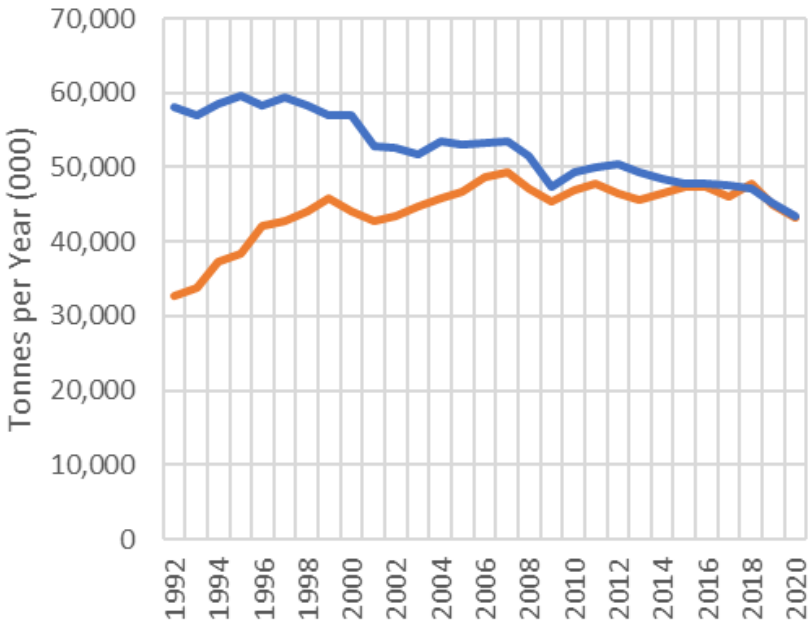
W. J. Sagues, [ab] H. Jameel,[a] D. L. Sanchez [c] and S. Park *[a]

Production from Virgin Pulp vs. Recycled Pulp

World Production



US Production



- World production from recycled pulp exceeded wood pulp in 2004
- In US, wood pulp production is declining, and it is now similar to recycled pulp production

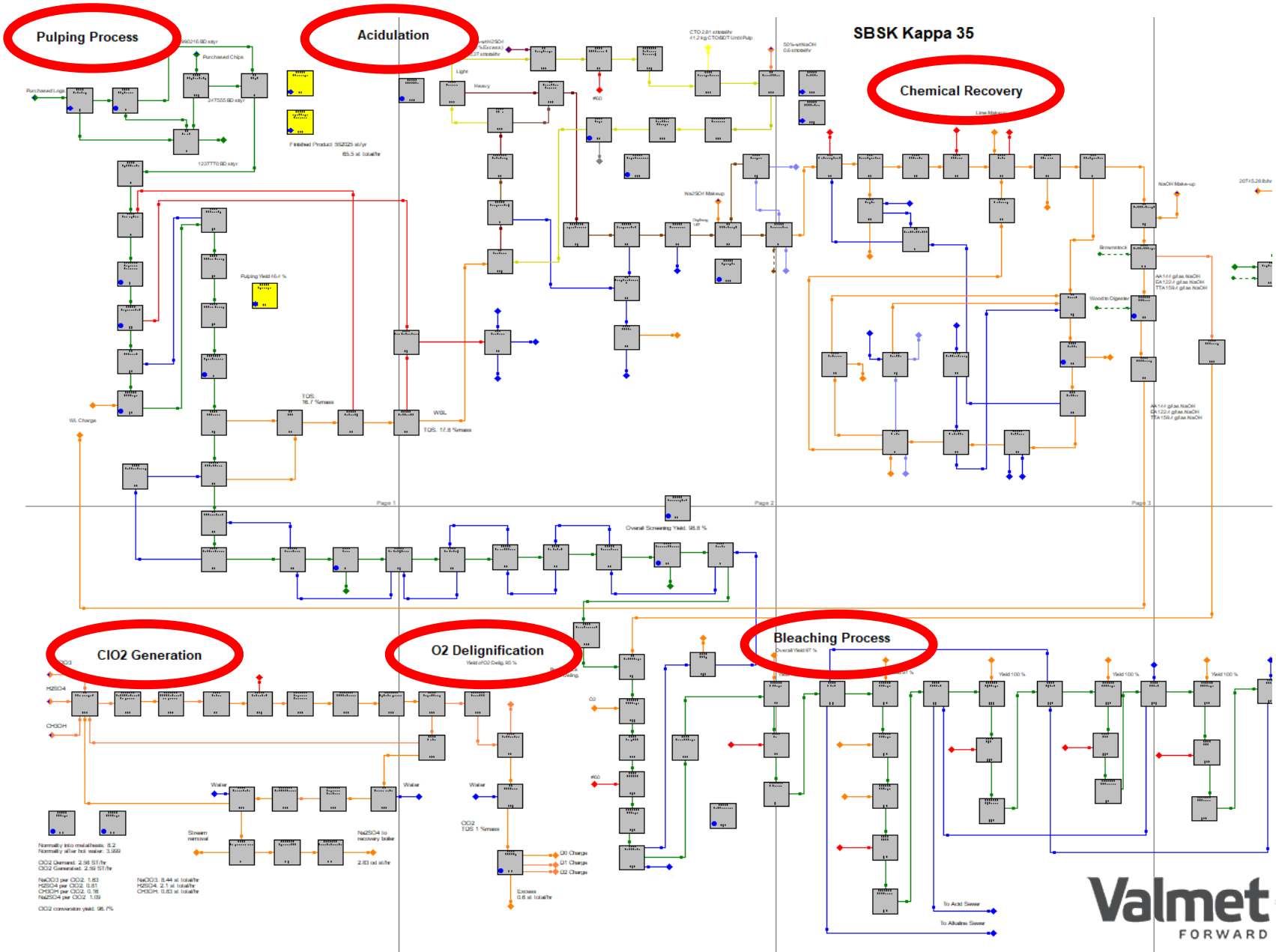
Pulp and Paper Mills in US (330 Sites)

FisherSolve® Next

Kraft Mill in US (91 Sites)

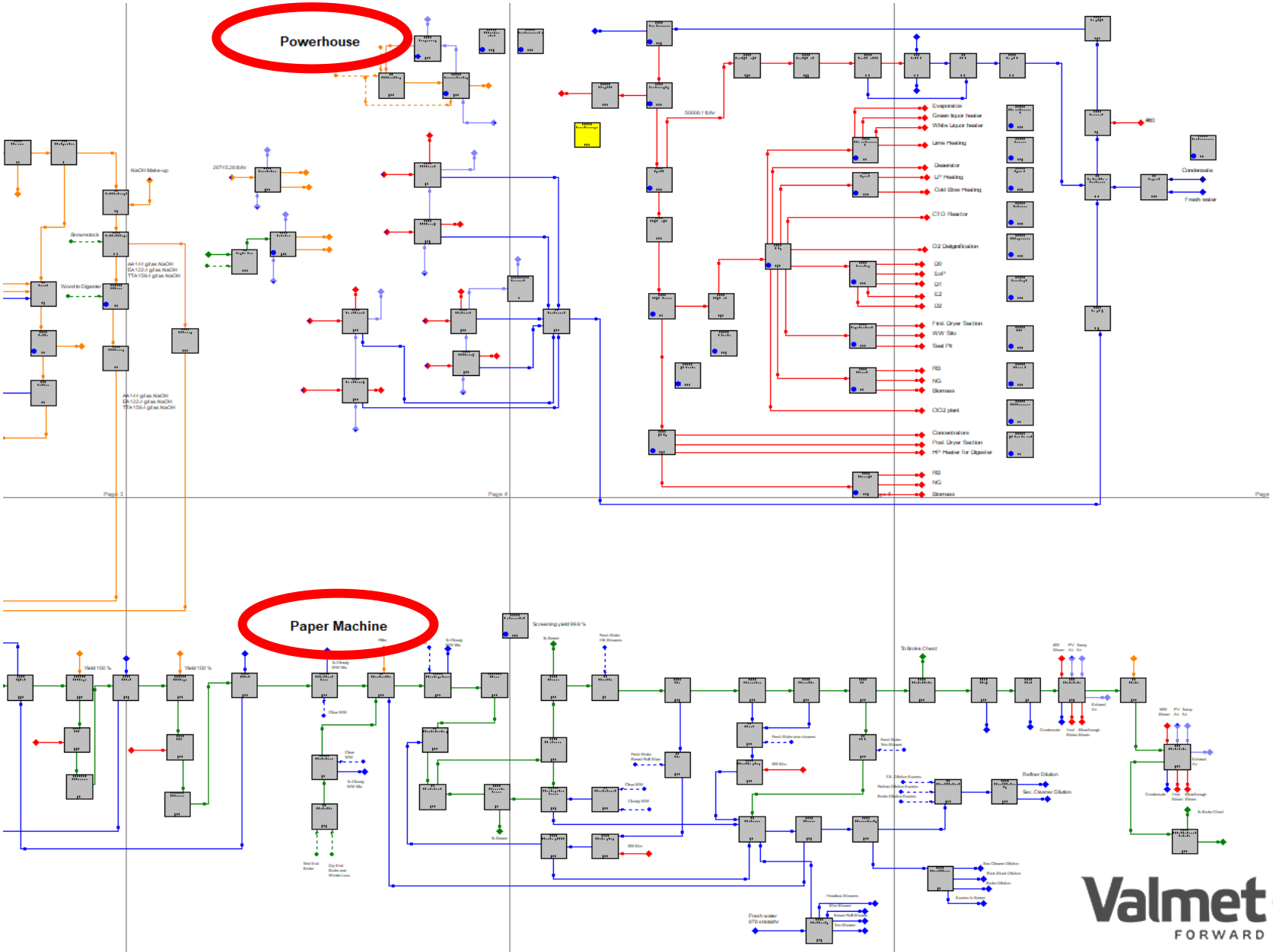
FisherSolve® Next

WinGEMS Process Simulation I



Valmet FORWARD

WinGEMS Process Simulation II



Valmet FORWARD

Southern Bleached Softwood Kraft (SBSK) Mill

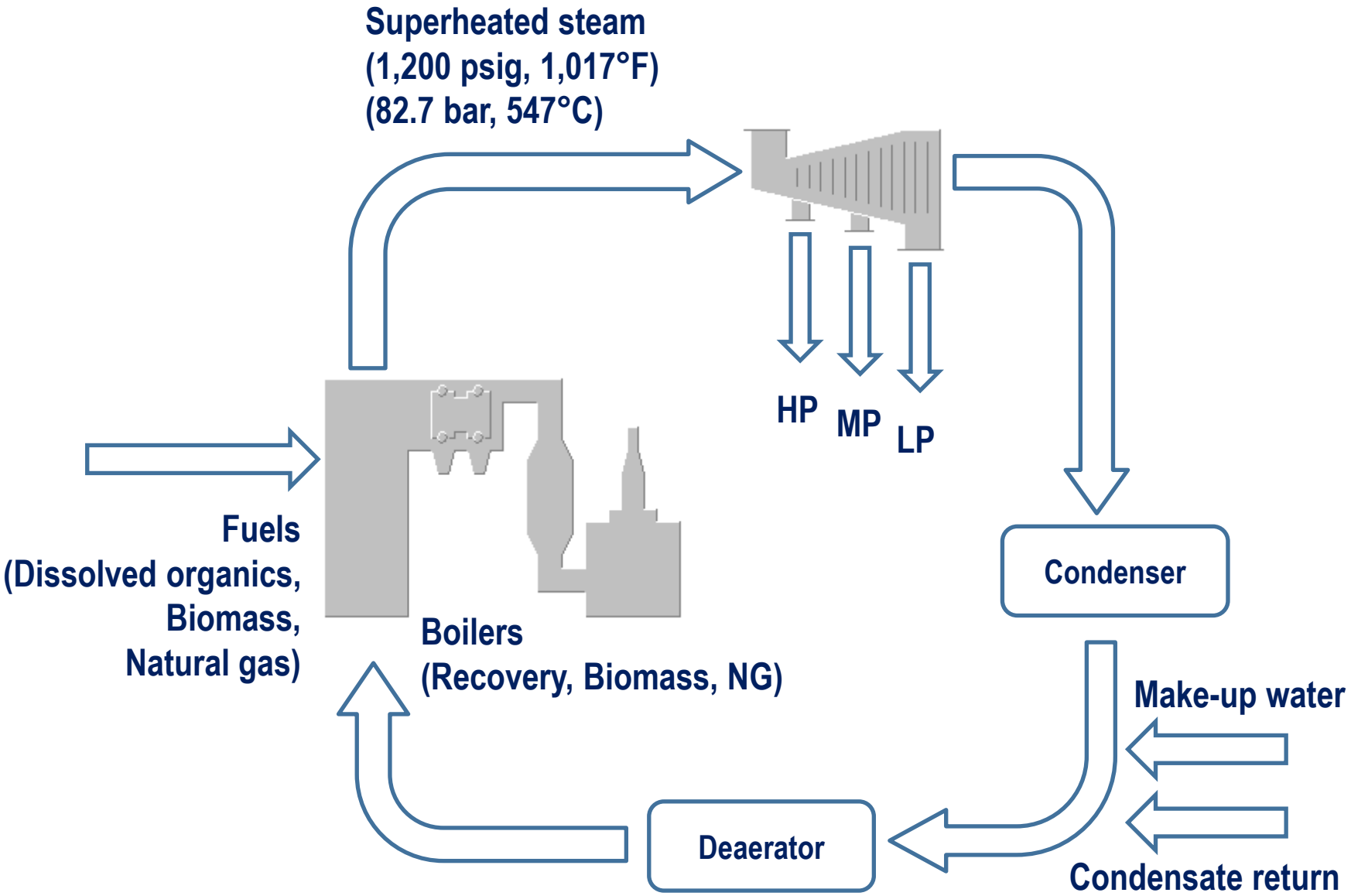
		Short ton	Metric ton
Raw Materials	Roundwood	990,218 od st/yr	898,311
		247,554 od st/yr	
	Total	1,237,772 od st/yr (3,526 od st/day)	1,122,888 (3,199 od mt/day)

Note: (od) oven dry, (ad) air dry, (st) short ton, (mt) metric ton

Assumption

- 80% roundwood + 20% chip purchase
- Annual operation: 351 days

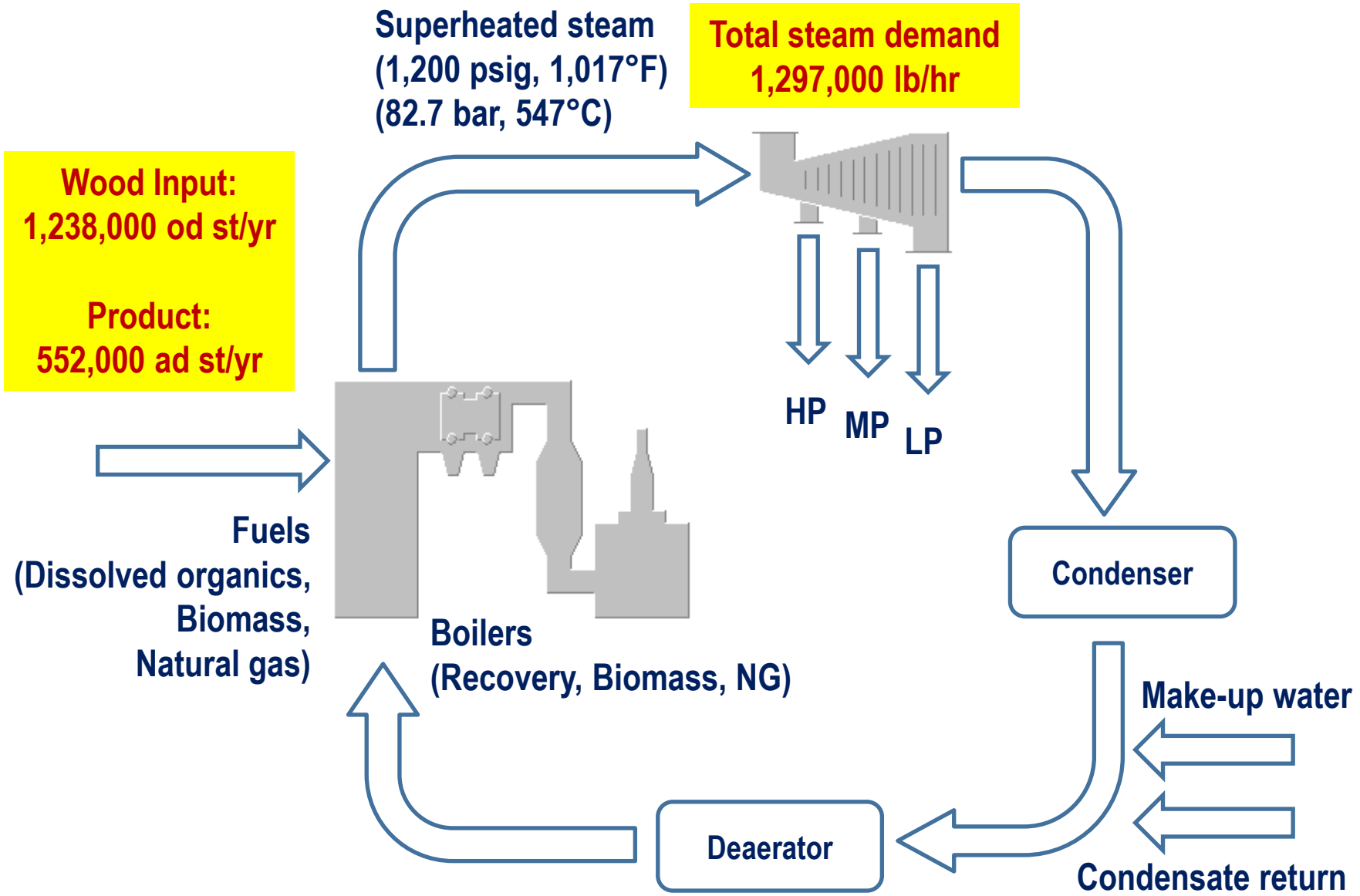
Powerhouse in Kraft Mill



Steam Demand for SBSK Mill

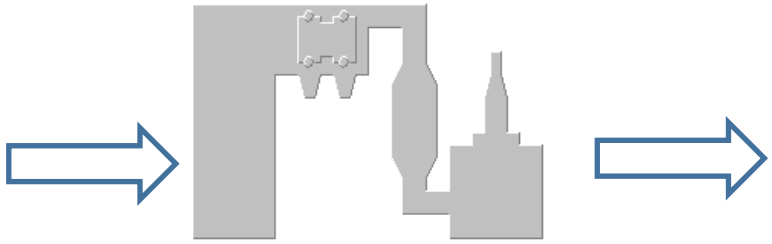
		400 psig lb/hr	160 psig, lb/hr	60 psig, lb/hr
Pulp mill	Digester (14.3%)	-	74,064	111,654
(49.5%)	Oxygen delignification	-	-	47,107
	Bleaching	-	-	103,398
	Evaporator (20.9%)	-	82,614	188,669
	ClO_2 plant	-	-	22,358
	Caustic plant	-	-	11,795
	Sub total	-	156,678	485,052
Paper mill	Dryer (13.4%)	-	84,267	89,609
(17.3%)	Hot water heating	-	-	50,067
	Sub total	-	84,267	139,676
Power plant	Sootblowing	50,000	-	-
(33.2%)	Air heater (RB, BB, NGB)	-	30,910	80,469
	Deaerator (17.0%)	-	-	220,115
	Condenser	-	-	50,000
	Sub total	50,000	30,910	350,584
	TOTAL	50,000	271,854	925,312
	TOTAL Steam Demand			1,297,173

Powerhouse in Kraft Mill



Three Types of Boiler in Kraft Mill

Dissolved organics
(e.g., lignin)

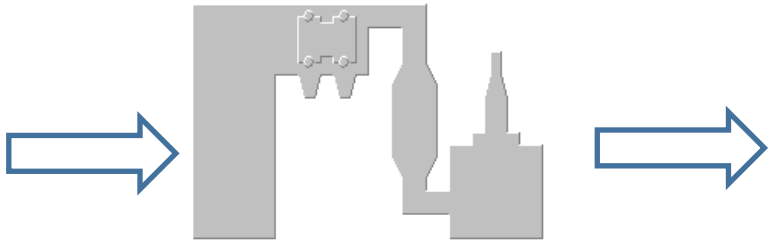


Recovery boiler (64% efficiency)

1,164 MMBTU/hr
(63.3%)

Biomass
(e.g., bark, screen reject)

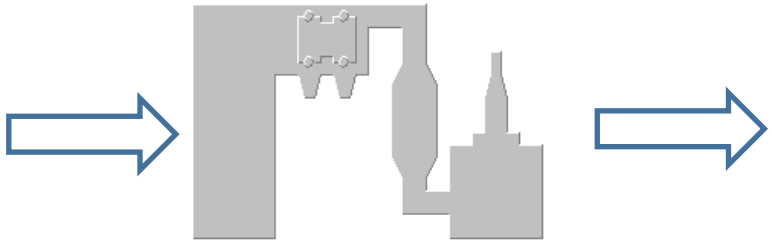
Assumed no hog fuel in this analysis



Biomass boiler (72% efficiency)

275 MMBTU/hr
(15.0%)

Natural gas

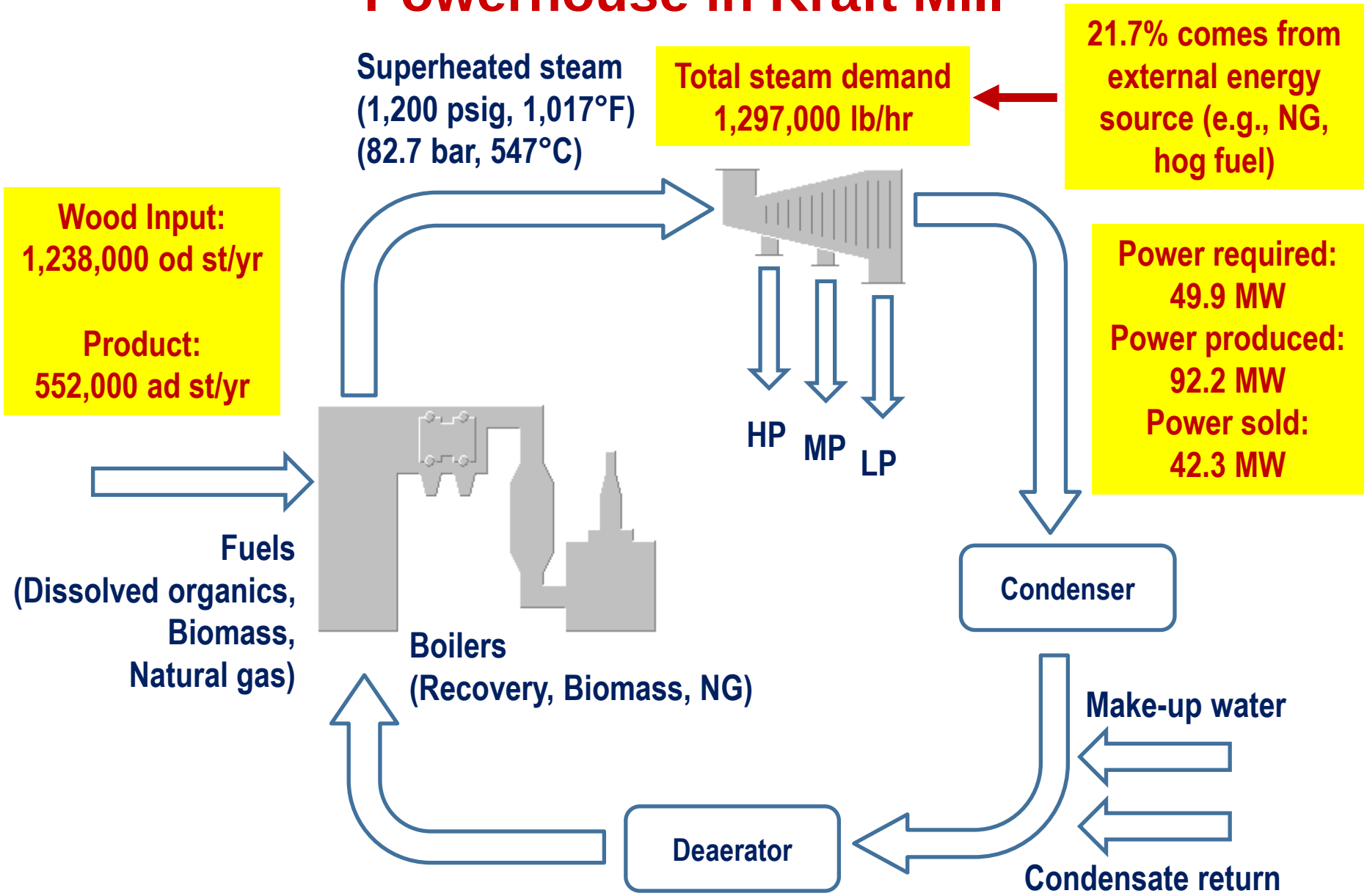


Natural gas boiler (82% efficiency)

399 MMBTU/hr
(21.7%)

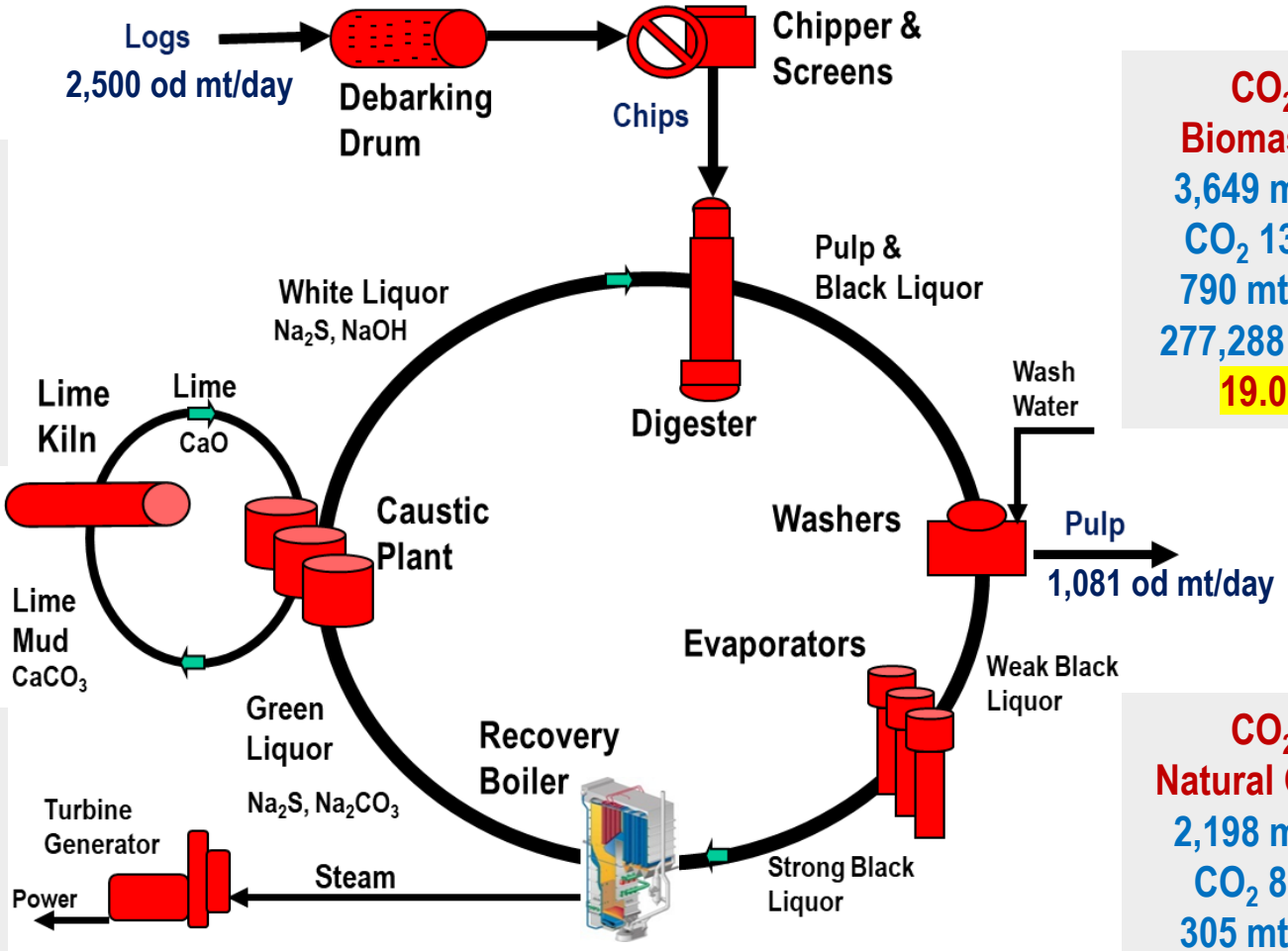
- A mill needs to purchase external energy (e.g., natural gas, hog fuel) in addition to internal energy (e.g., dissolved organics, bark, screen reject).
- Total enthalpy to steam is 1,839 MMBTU/hr to meet the steam demand (1,297,000 lb/hr)

Powerhouse in Kraft Mill



CO_2 from Kraft Mill: Typical SBSK Mill

CO_2 from Lime Kiln
1,096 mt FG/day
CO_2 19.4 mol%
331 mt CO_2/day
116,071 mt CO_2/yr
7.9% CO_2



CO_2 from Biomass Boiler
3,649 mt FG/day
CO_2 13.5 mol%
790 mt CO_2/day
277,288 mt CO_2/yr
19.0% CO_2

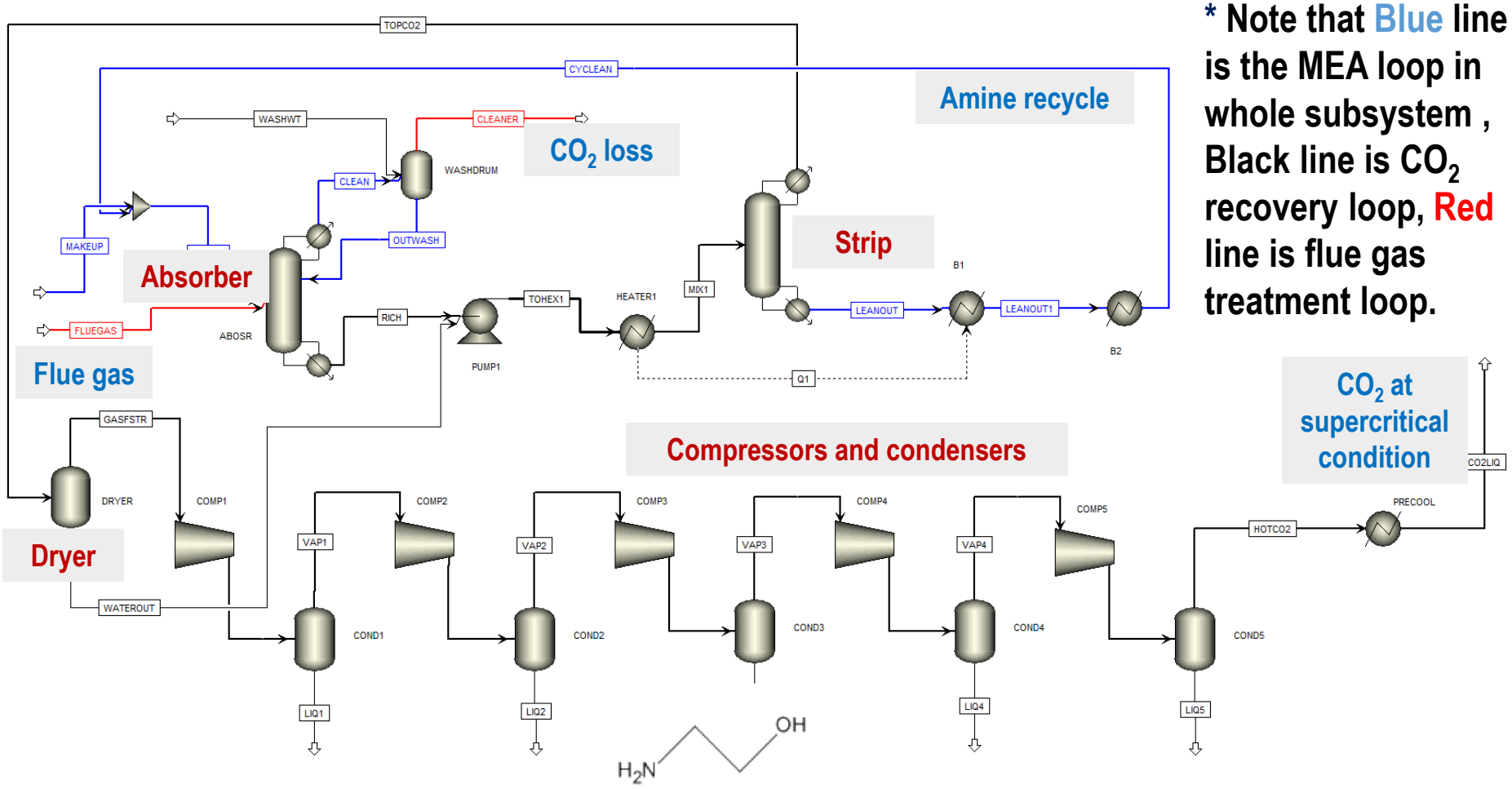
CO_2 from Recovery Boiler
13,096 mt FG/day
CO_2 11.3 mol%
2,742 mt CO_2/day
962,572 mt CO_2/yr
65.8% CO_2

CO_2 from Natural Gas Boiler
2,198 mt FG/day
CO_2 8.7 mol%
305 mt CO_2/day
107,060 mt CO_2/yr
7.3% CO_2

SBSK vs. SBHK vs. UBSK

	Softwood Bleached Kraft (SBSK)	Hardwood Bleached Kraft (SBHK)	Softwood Unbleached Kraft (UBSK)
Wood fiber, od mt/day	2,500	2,500	2,500
Pulping Kappa #	35	17	100
Production, FT/day	1,104	1,223	1,607
Steam production, lb/hr	854,630	807,600	891,700
Lime Kiln, mt CO_2/yr	104,464	94,044	89,149
Recovery boiler, mt CO_2/yr	866,314	834,405	667,803
Biomass boiler, mt CO_2/yr	249,559	232,835	249,559
Natural gas boiler, mt CO_2/yr	96,354	94,465	217,270
Total CO_2, mt CO_2/yr	1,316,691	1,255,749	1,223,781
Total CO_2, mt CO_2/FT production	3.27	2.81	2.09
Total CO_2, mt CO_2/mt product	3.91	3.37	2.50

Amine CO_2 Capture Technology

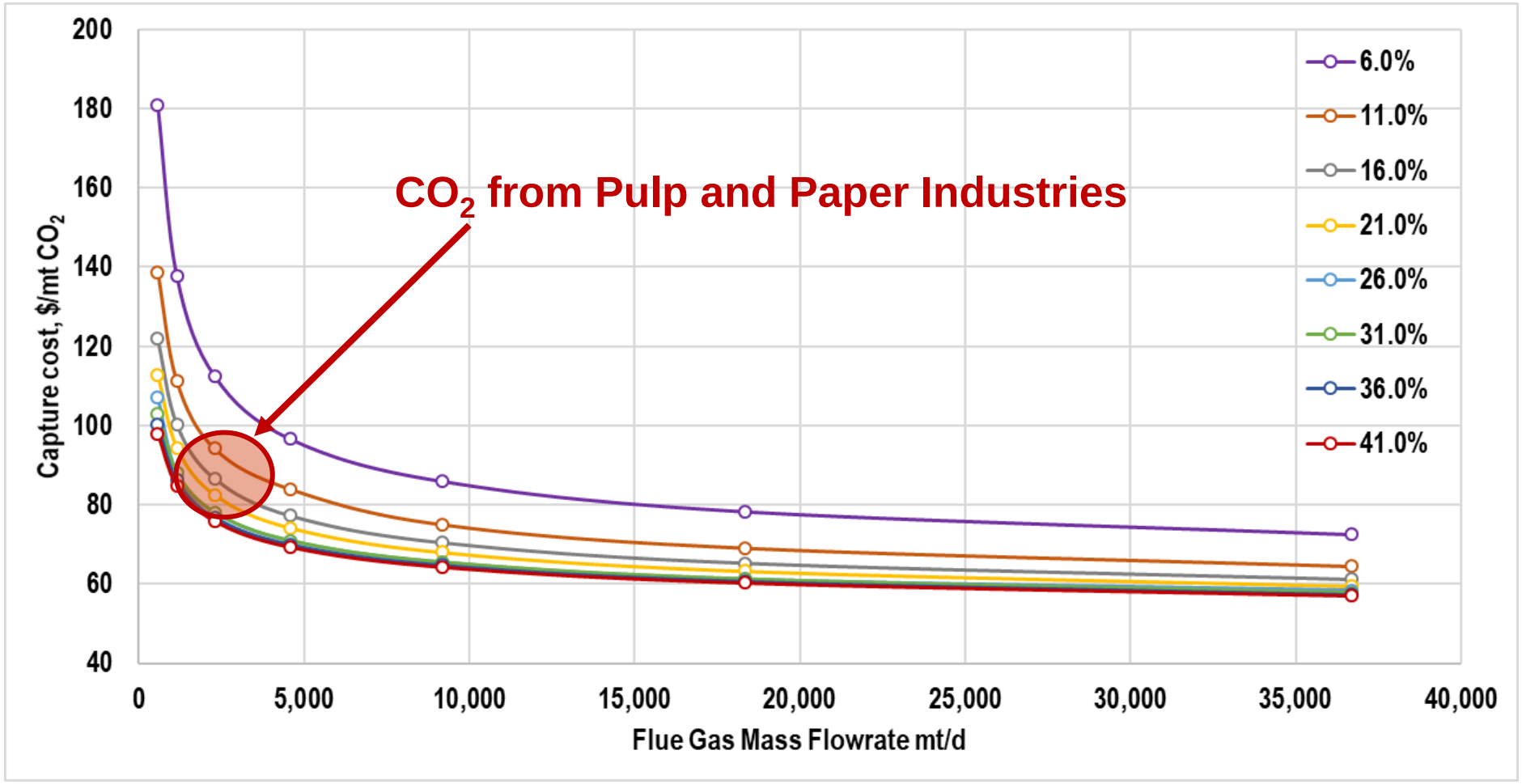


* Note that Blue line is the MEA loop in whole subsystem , Black line is CO_2 recovery loop, Red line is flue gas treatment loop.

30% monoethanolamine (MEA)
90% CO_2 capture efficiency
153 bar pressure & 44.4 ℃ temperature

CO_2 supercritical point
73.9 bar & 31.1 ℃

$/mt CO_2 vs. Flue Gas flowrate and CO_2 Conc.



45Q Tax Credit

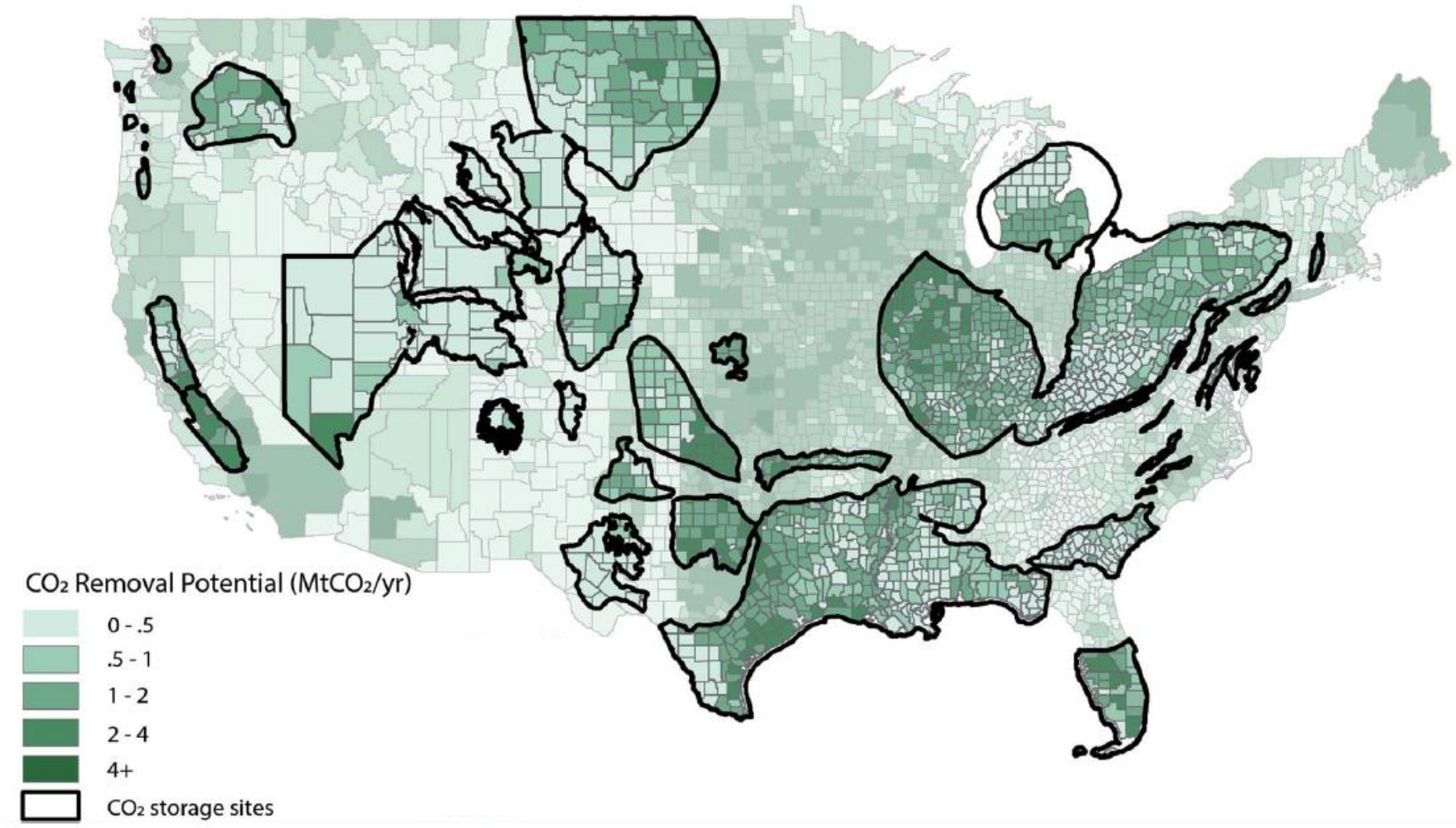
Minimum size of eligible carbon capture plant by type ($ktCO_2$/year)

	Power Plants[1]	Other facilities	Direct Air Capture (DAC)	Construction begins after 8/16/22
Dedicated Geological Storage	18.75	12.5	1	$85 ($180 DAC)
Storage via Enhanced Oil Recovery	18.75	12.5	1	$60 ($130 DAC)
Other Qualified Use of CO2	18.75	12.5	1	$60 ($130 DAC)

[1]Amount captured o utilized must be ≥ 75% baseline carbon oxide production.

chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://sgp.fas.org/crs/misc/IF11455.pdf

Potential Geologic Storage Sites for CO_2



W.J. Sagues, S. Park, H. Jameel, D.L. Sanchez*, Enhanced carbon dioxide removal from coupled direct air capture-bioenergy systems, Sustainable Energy & Fuels, 3: 3135-3146 (2019)

CO_2 Reduction Potential in P&P Industry I

- **Non-kraft mill** (Recycled Linerboard, Tissue and Towel)
  - Dryer operation will be the major energy user
    - Solid content (exiting press section), dyer thermal efficiency, and alternative energy source for dryer.

- **Kraft mill**
  - Natural gas and biomass boiler
    - 21.7% steam is produced from NG boiler
    - 15.0% steam is produced from biomass boiler
    - Key is how to reduce steam demand in the process
  - Lime kiln
  - Recovery boiler

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		400 psig lb/hr	160 psig, lb/hr	60 psig, lb/hr
Pulp mill	Digester (14.3%)	-	74,064	111,654
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	Sub total	50,000	30,910	350,584
	TOTAL	50,000	271,854	925,312
	TOTAL Steam Demand			1,297,173

CO_2 Reduction Potential in P&P Industry II

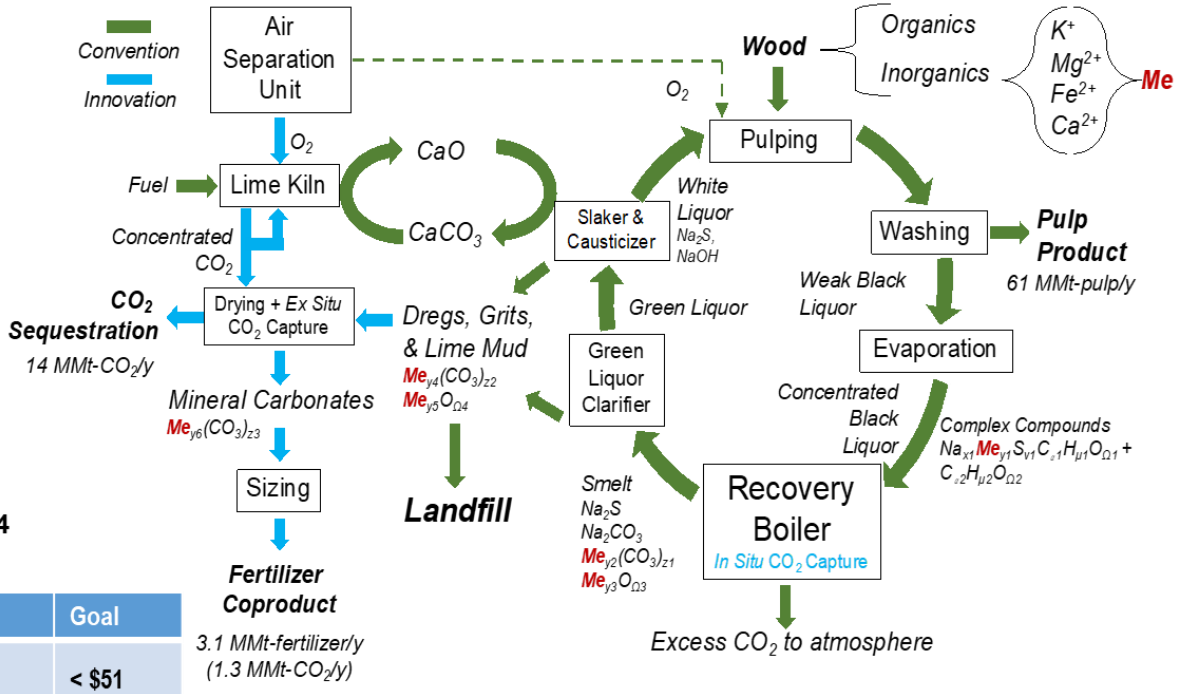
- **Kraft mill - Lime kiln** (on-going project example)

Integrating Carbon Capture, Utilization, & Sequestration into Chemical Pulp Mills

The goal of this project is to demonstrate the techno-economic feasibility of an integrated technology of low capital intensity that will capture, utilize, and sequester CO_2 in chemical pulping processes

PI: Dr. William (Joe) Sagues

Requested funds: $1,273,054
Cost share: 20.34%



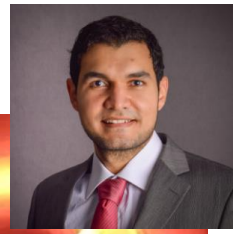
Cumulative mass flows for US pulp industry

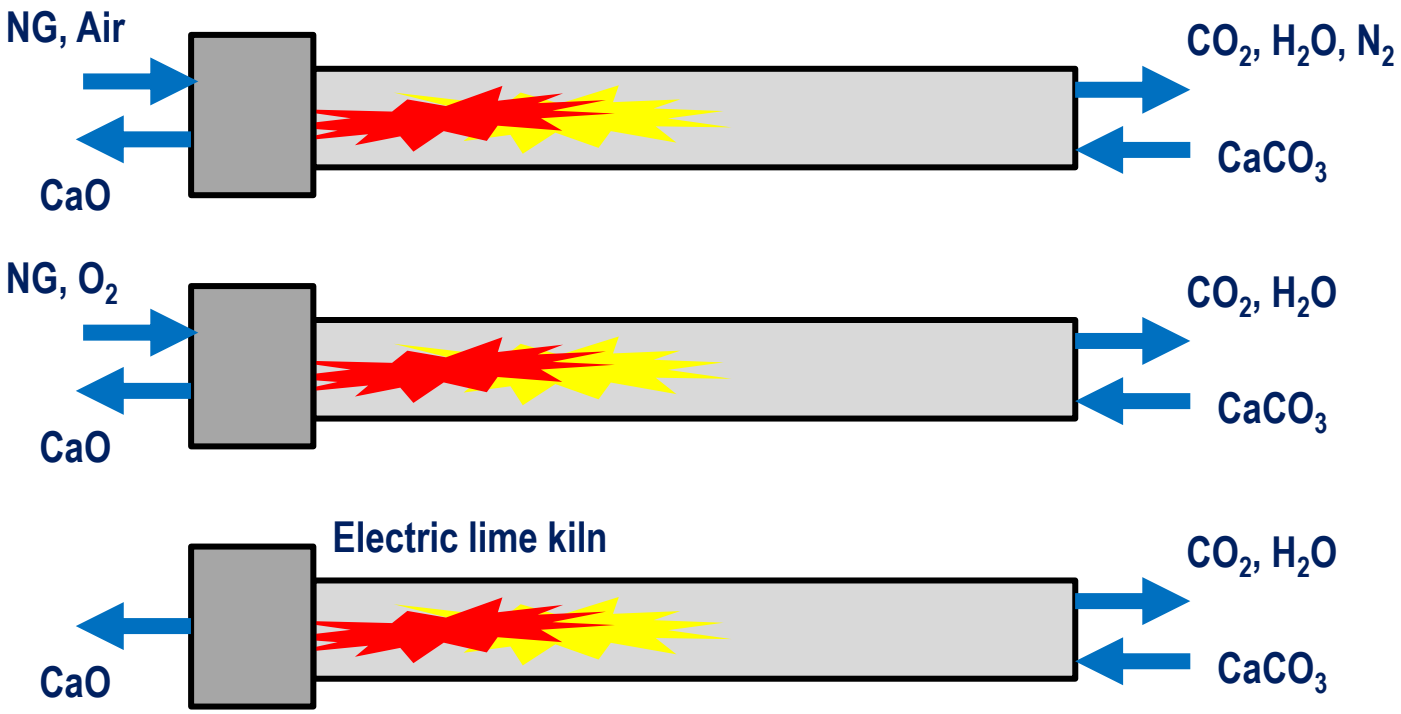
Metric	Goal
Cost of Fertilizer (USD per tonne fertilizer)	< $51
Carbon Intensity of Fertilizer (tonne CO_2 per tonne fertilizer	< 0.4
Cost of sequestered CO_2 (USD per tonne CO_2)	< $50
Carbon Intensity of Pulp Product (tonne CO_2 per tonne pulp product)	< 1.9

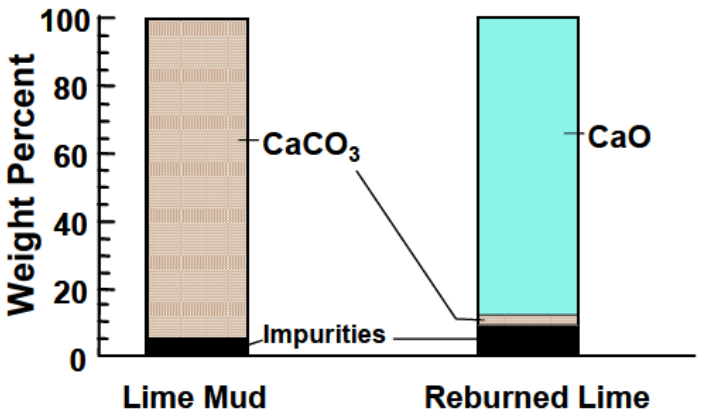
Impact in US Pulp Industry
~15.3 MMtCO_2/y captured, utilized, & sequestered
Fertilizer co-product: ~14% market penetration

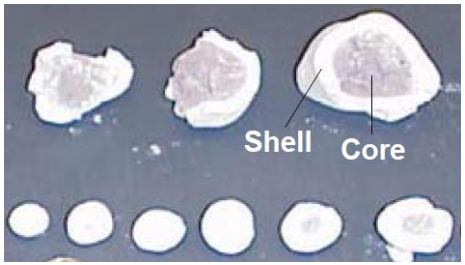
NC STATE UNIVERSITY Berkeley UNIVERSITY OF CALIFORNIA

Electric Lime Kiln









CO_2 Reduction Potential in P&P Industry III

- **Kraft mill – Recovery Boiler**

- With alternative pulping
  - New solvent pulping – currently lab R&D stage
  - DOE project example (under negotiation with DOE-IEDO)

- With kraft pulping
  - How to recover kraft chemicals (NaOH and Na_2S)
    - Membrane (DOE proposal pending), Reduction furnace

- What to do with dissolved organics (i.e., lignin)?
  - Biofuels, adhesives, epoxy resins, cement, and others

- The mentioned technologies might be suitable for small-scale pulping mills to produce alternative fibers (especially non-wood fibers), where the kraft process with a recovery boiler ($200+ million) is too expensive.

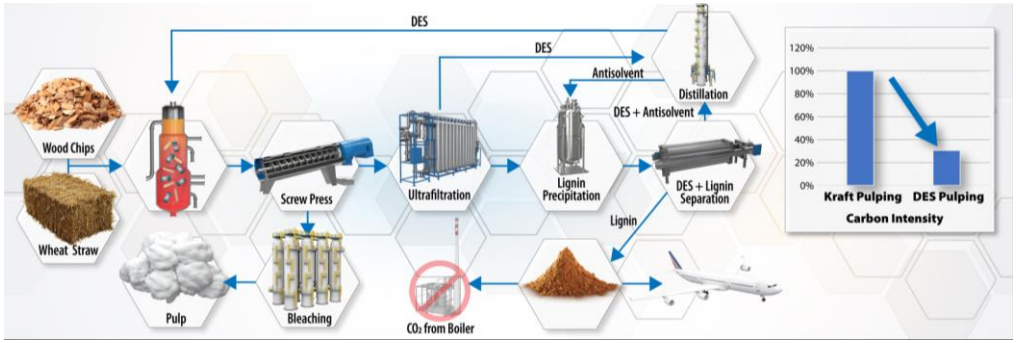
Deep Eutectic Solvent Pulping Technology to Reduce Carbon Emission

Technical POC: Sunkyu Park, NCSU (Lead), Xiaowen Chen, NREL

Technology Summary

This project aims to develop and optimize low-carbon intensity Deep Eutectic Solvent (DES) pulping technology by replacing a recovery boiler in a conventional kraft pulp mill. The kraft process has dominated the pulping industry for over 100 years. The process is currently favored due to superb pulp yields, paper properties, and efficient chemical recovery. However, kraft processes suffer from high CO_2 emissions due to lignin combustion in the recovery boiler. The pulp mills in the US emits ~150 million metric tons of CO_2/yr, and the combustion of lignin in the recovery boiler accounts for over 65% of overall CO_2 emissions. In this project, we propose reinventing the kraft pulping process to reduce greenhouse gas (GHG) emissions by replacing it with a low-GHG emission DES pulping process. The proposed process will produce dissolving pulp and lignin useful for the production of bio-based materials, chemicals, and biofuels, which will further reduce GHG emissions through displacement for fossil-based products. Specifically, we will (a) develop and optimize the sulfur-free DES pulping and chlorine-free bleaching process to produce high-quality dissolving pulp, (b) perform membrane ultrafiltration to reduce the amount of anti-solvent usage by concentrating lignin with different molecular weights, (c) optimize DES recovery process via anti-solvent precipitation and distillation process, (d) produce high-quality viscous-grade dissolving pulp and sulfur-free lignin, (e) conduct a rigorous techno-economic analysis and life cycle assessment to evaluate the economic and environmental benefits based on the integrated experimental results, and (d) stimulate underserved students' interest in career pathways in the bioeconomy.

Process Overview



Key Personnel

Park, Venditi, Blanchard, Jameel (NCSU), Chen, Chen (NREL), Zhang (WSU), Shi, Escobar (UK), Tunc, Wang (Sappi)

Program Summary

Period of performance: 36 months

Federal funds:	$ 2,600,000
Cost-share:	$ 750,000
Total budget:	$ 3,350,000

Key Deliverables and Matrix

	BP1	BP2
Removal of non-cellulosic components, %	80	90
Solvent recovery, %	90	95
ISO Brightness of dissolving pulp, %	87	91.5
Minimum selling DP price to DP market, %	140	100
Cost of avoided carbon, $/mt CO_2	140	100
Reduction in carbon intensity (ton CO_2e/kg), %	50	70
DEI training for project researchers, %	100	-
Create 3 high school hands-on activities, %	100	-
Engage 250 high-school students, %	-	100

Technology Impact

The success of DES pulping technology will lead to the evolution of pulping technology toward a greener and safer process by eliminating the need for lignin combustion and sodium recovery, which is required in the traditional kraft pulping process. The elimination of the recovery boiler and lime kiln, which represents over a $400 million capital investment, is a game changer for the current pulping process. EERE funding would allow the team to improve the performance of the DES pulping technology in multiple dimensions, including solvent recovery, energy reductions, and product development. In addition, we will create opportunities for underserved students in rural high schools to learn about pulp and paper, the circular bioeconomy, and related careers, encouraging a pipeline of new people to pursue careers in these areas.

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Acknowledgements

Current People	Status
Song Wang	Postdoc Researcher
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