

TOWARD A NET ZERO FUTURE IN THE FOREST PRODUCTS INDUSTRY

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About NCASI:

NCASI (National Council for Air and Stream Improvement, Inc.) is a non-profit environmental research organization that seeks to create credible scientific information to address the environmental information needs of the forest products industry in North America. NCASI conducts surveys, performs field measurements, undertakes scientific research, and sponsors research by universities and others to document the environmental performance of industry facility operations and forest management, and to gain insight into opportunities for further improvement in meeting sustainability goals.

TOWARD A NET ZERO FUTURE IN THE FOREST PRODUCTS INDUSTRY

EXECUTIVE SUMMARY

The forest products industry has unique opportunities and constraints associated with designing an achievable strategy for attaining net zero, along with site-specific aspects that lead to company-specific analyses, strategies, and decisions as to whether to commit to achieving net zero, and by what date. Net zero refers to reducing greenhouse gas emissions as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere, by oceans or forests, for instance¹. Net zero targets have been made by governments in the United States, Canada, China, and the European Union, among others, and currently cover approximately 76% of global emissions. This NCASI white paper provides an overview of decarbonization technologies that could enable achievement of net zero, along with calculations of the resources and costs that may be required to reduce and/or offset the current industry greenhouse gas (GHG) profile.

Reviewed decarbonization technologies and approaches are structured around the following pillars of decarbonization:

- Energy efficiency including combined heat and power utilization
- Manufacturing of low-carbon fuels, feedstocks, and energy sources
- Carbon capture, utilization, and storage
- Electrification of heat

Forest product applications of decarbonization technologies within each of the decarbonization pillars are highlighted. Policy issues around incentivizing decarbonization technologies utilizing biomass are reviewed, as well as the potential impacts to biomass supplies if wide-scale bio-based decarbonization approaches are adopted within the US forest products industry.

KEYWORDS

Net zero, decarbonization, greenhouse gas emissions, pulp and paper industry, wood products sector, forest products industry

¹ Definition published by United Nations Net Zero Coalition (<https://www.un.org/en/climatechange/net-zero-coalition>) (June 2023)

Table of Contents

1.0	Introduction	13
2.0	Background on the US Forest Products Sector	13
3.0	The Pillars of Decarbonization for the US Forest Products Sector	16
4.0	Energy Efficiency Including Combined Heat and Power Utilization	17
4.1	Combined Heat and Power	19
5.0	Low-Carbon Fuels, Feedstocks, and Energy Sources	20
5.1	Biomass Power Boilers	22
5.2	Biomass Utilization in Lime Kilns	22
5.3	Grid Decarbonization	28
5.4	Greening of Steam Generators	31
6.0	Carbon Capture and Storage or Use (CCS/U)	33
6.1	Chemical Absorption Post-Combustion Techniques	33
6.2	Membrane Separation	44
6.3	Chemical Looping	45
6.4	Cryogenic Carbon Capture	47
6.5	Direct Air Capture	50
6.6	Pre-Combustion Techniques	51
6.7	Oxy-Combustion	52
6.8	Comparison of Carbon Capture Techniques	54
6.9	Bioenergy Carbon Capture	62
6.10	Enzyme Enhancement	65
6.11	Storage and Transport of CO ₂	65
7.0	Electrification of Heat	66
7.1	Electric Boilers	68
7.2	Infrared Drying of Paper	71
7.3	Industrial Heat Pumps	73
7.4	Electric Lime Kiln	77
7.5	Economics of Electrification of Heat	77

8.0	Policy Issues for Carbon Programs	79
9.0	Potential Effects on the Biomass Supply	82
	References	86

Figures

Figure 1. Changes in Total Fenceline Energy Intensity Over Time from AF&PA/API and EIA MECS Data for the US Pulp and Paper Sector (NCASI 2021a).....	18
Figure 2. Changes in Total Fenceline Energy Intensity Over Time and Changes in Biomass and Fossil Energy Share from AF&PA/API data (NCASI 2021a)	18
Figure 3. Onsite Energy Mix Over Time for the US Pulp and Paper Industry Based on EIA MECS Data (NCASI 2021a).....	20
Figure 4. Onsite Energy Mix Over Time for the US Pulp and Paper Industry Based on AF&PA/API Data (NCASI 2021a)	21
Figure 5. Onsite Energy Mix Over Time for the US Wood Products Sector Based on EIA MECS Data	21
Figure 6. Distribution of Lime Kiln Fuel Consumption at US Mills	24
Figure 7. Distribution of Lime Kiln Fuel Consumption from NCASI and International Surveys	24
Figure 8. Schematic of a Pulp Mill Biomass Gasification System.....	25
Figure 9. Relationship Between Gasifier Size (MW) and Lime Throughput.....	28
Figure 10. Average US Electrical Grid GHG Emission Factor Over Time Based Upon eGRID.....	29
Figure 11. The Percent of Total Renewables Generation Over Time	29
Figure 12. Projections for US Electric Grid Carbon Intensity	30
Figure 13. US Grid Additions/Retirements Annual Energy Outlook 2022	31
Figure 14. Purchased Steam Emission Factors Over Time	32
Figure 15. Block Flow Diagram of a Post-Combustion CO ₂ Capture Plant.....	34
Figure 16. MEA Regeneration Energy as a Function of Absorber Packing Height	36
Figure 17. MEA Regeneration Energy	37
Figure 18. Low Pressure Steam Requirements as a Fraction of Mill CO ₂ Emissions for a Kraft Market Pulp Mill	38
Figure 19. Electricity Requirements as a Fraction of Mill CO ₂ Emissions for a Kraft Market Pulp Mill	38
Figure 20. Low Pressure Steam Requirements as a Fraction of Mill CO ₂ Emissions for an Integrated Market Pulp and Board Mill	39
Figure 21. Electricity Requirements as a Fraction of Mill CO ₂ Emissions for an Integrated Market Pulp and Board Mill	40
Figure 22. Process Flow Schematic for the Chilled Ammonia Process Modeling	41
Figure 23. Energy Requirements as a Function of the Loading in the CO ₂ Rich Stream	42

Figure 24. Energy Requirements as a Function of Initial Mass Fraction of Ammonia 43

Figure 25. Schematic of a Chilled Ammonia Carbon Capture System from Alstom 44

Figure 26. Gas Separation with Membranes 44

Figure 27. Schematic for a Membrane Separation Process..... 45

Figure 28. Schematic of a Carbonate Looping Process 46

Figure 29. Schematic of a Calcium Looping Process 47

Figure 30. Schematic of a Cryogenic Distillation System 48

Figure 31. Cryogenic CO₂ Capture Process Using Stirling Coolers 49

Figure 32. Orca Direct Air Capture Facility in Hellisheiði, Iceland. 50

Figure 33. Post-Combustion CO₂ Removal..... 51

Figure 34. Pre-Combustion CO₂ Removal 52

Figure 35. Schematic of an Oxyfuel Combustion Process..... 52

Figure 36. Oxyfuel Combustion Process with add-on Carbon Capture 53

Figure 37. Approximate Lowest Cost Oxygen Supply Methods for New Plants 53

Figure 38. TRL Distribution of Ninety-Two Post-Combustion CO₂ Captures Processes..... 61

Figure 39. TRL Distribution of Eighty-Eight Post-Combustion CO₂ Capture Processes in 2016..... 62

Figure 40. MHI's Post-Combustion Amine-Based Carbon Capture System being Used at
Drax Power Station in North Yorkshire, England 63

Figure 41. Resolute Saint-Félicien Pulp Mill and Serres Toundra’s Vegetable Greenhouse..... 64

Figure 42. US Map of Potential Sink Locations and Capacity..... 65

Figure 43. Typical Steam Properties and Uses at Chemical Pulp Mills 67

Figure 44. Schematic of the PARAT IEH Electrode Boiler and Hot Water System. 69

Figure 45. Distribution of "Other" Fuels Used in US Industrial Combustion Boilers (tCO₂/GJ) 70

Figure 46. Distribution of "Other" Fuels Used in US Industrial Combustion Boilers (tCO₂/GJ) 71

Figure 47. Infrared Heating for Paper Drying (Beyond Zero Emissions 2018) 72

Figure 48. Andritz PrimeDry Hood E Electrically Heated Hood for Tissue Machines 72

Figure 49. Voith qDry Pro Non-Contact Dryer 73

Figure 50. Voith qDry Pro Non-Contact Dryer Available Configurations 73

Figure 51. Thermodynamic Representation of Industrial Heat Pump 74

Figure 52. Process Heat Demand for Select Industrial Sectors in 2014..... 75

Figure 53. VTT’s Electric Rotary Lime Kiln 77

Figure 54. Thermal Generation Costs from Common Fuels..... 78

Figure 55. 2021 Biogenic CO ₂ Emissions from US Pulp and Paper Facilities.....	82
Figure 56. US Pulp and Paper Mills with Biogenic CO ₂ Emissions.....	83
Figure 57. Production of Forest Products in the Southeastern United States Over Time	84

Tables

Table 1.	The US Pulp and Paper Sector's Manufacturing-Related Greenhouse Gas Profile.....	14
Table 2.	US Wood Products Sector's Manufacturing-Related Greenhouse Gas Profile	14
Table 3.	Greenhouse Gas Emission Distribution by Major Pulp and Paper Mill Type	17
Table 4.	Greenhouse Gas Emission Distribution by Major Wood Product Facility Type	17
Table 5.	US Forest Products Industry Installed CHP Capacity.....	19
Table 6.	The US Forest Products Industry Electricity Generation Profile	19
Table 7.	Biomass Residual Utilization in Power Boilers in the US Forest Products Sector in 2018	22
Table 8.	Heat Rate (GJ HHV/mt CaO) Statistics for Lime Kiln Operation	23
Table 9.	Fuel Distribution on an Energy Basis for US Lime Kilns.....	25
Table 10.	Heating Value Comparison of Fossil Fuels and Gasified Wood Residuals	26
Table 11.	Lime Kiln Biomass Gasification Installations at Pulp and Paper Mills	27
Table 12.	Purchased Electricity GHG Profile for the US Forest Products Industry	28
Table 13.	Projections for the US Forest Products Industry Scope 2 Emissions Due to Continuing Greening of the Electrical Grid	30
Table 14.	Purchased Steam Emission Factors for Kraft Pulp and Paper Mills	32
Table 15.	Typical Impurities in the Pulp and Paper Flue Gases (reported @ 6% O ₂ , dry)	35
Table 16.	Process Conditions for the Chilled Ammonia System in the Patent by Gal (2006).....	41
Table 17.	Absorber Operating Configuration	41
Table 18.	Desorber Operating Configuration	42
Table 19.	Energy and Economic Summary of Studies from Membrane-Based CO ₂ Separation Processes	45
Table 20.	Energy Needs for Various Carbon Capture Methods.....	49
Table 21.	Energy Requirements for Oxygen Production	54
Table 22.	Basic Properties of MEA and NH ₃	54
Table 23.	Comparison of Classes of Carbon Capture Technologies	55
Table 24.	Efficiency Losses and Costs Associated with Classes of Carbon Capture Technologies	56
Table 25.	Effect on Power Plant Efficiency by Installation of Post-Combustion Carbon Capture	56
Table 26.	Comparison of Post-Combustion Carbon Capture Technologies	58
Table 27.	EPRI TRL Definitions for Use with CO ₂ Capture Processes	60
Table 28.	Technology Readiness Levels of Carbon Capture Technologies	61

Table 29. Fenceline Thermal Loads for Pulp and Paper Operations.....	66
Table 30. Annual Energy Demand by Forest Products Industry Boiler Capacity in 2018	69
Table 31. Industrial Heat Pump Types	76
Table 32. Proposed Policy Approaches to Facilitate Adoption of Net Negative Technologies like BECCS.....	80
Table 33. Biogenic CO ₂ Emission Statistics for US Pulp and Paper Mills	83
Table 34. State Level Calculations for Lime Kiln Biomass Gasification, Bioenergy Carbon Capture Adoption, and Effect on Available Biomass Supplies to Achieve Net Zero Operation (balancing of combustion and process GHG emissions).....	85

Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
CA	Carbonic Anhydrase
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCS/U	Carbon Capture and Storage and/or Use
COP	Coefficient of Performance
COP26	26th UN Climate Change Conference of the Parties
CDR	Carbon Dioxide Removal
DAC	Direct Air Capture
DACCS	Direct Air Capture and Carbon Storage
ECBM	Enhanced Coal Bed Methane
EGR	Enhanced Gas Recovery
EIA MECS	US Energy Information Administration Manufacturing Energy Consumption Survey
EOR	Enhanced Oil Recovery
EPRI	Electric Power Research Institute
GHG	Greenhouse Gas
GGR	Greenhouse Gas Removals
IHP	Industrial Heat Pump
IRA	Inflation Reduction Act
MEA	Monoethanolamine
MO	Mineral Oxide
MVC	Mechanical Vapor Compression
MVR	Mechanical Vapor Recompression
NET	Negative Emission Technology
PC	Pulverized Coal
OPEX	Operational Expenditure
SCOP	Seasonable Coefficient of Performance

TRL	Technology Readiness Level
TVR	Thermal Vapor Recompression
USC	Ultra Super Critical
WWT	Wastewater Treatment

TOWARD A NET ZERO FUTURE IN THE FOREST PRODUCTS INDUSTRY

1.0 Introduction

“Net Zero” is generally defined as either zero greenhouse gas (GHG) emissions or the removal of an equivalent amount of GHG as was emitted. Dozens of countries, hundreds of cities, thousands of businesses, investors, and higher education institutions have committed to achieving net zero – a commitment that has expanded after the 26th UN Climate Change Conference of the Parties (COP26). The origin of the “net zero” concept was the Paris Agreement, a legally binding international treaty to limit the rise in mean global temperature to well below 2°C above pre-industrial levels, and preferably limit the increase to 1.5°C. As part of the Paris Agreement, countries provide nationally determined contributions (NDCs) that detail the country’s emission reduction goals. Several NDCs have net zero 2050 goals. The concept of “net zero” was further elucidated in a 2018 IPCC special report on the impacts of global warming of 1.5°C². Within the report, IPCC said “global net human-caused emissions of carbon dioxide (CO₂) would need to fall by about 45 percent from 2010 levels by 2030, reaching ‘net zero’ around 2050.” The Science Based Targets initiative (SBTi) operationalized the concept of net zero for companies and organizations. Targets adopted by companies and organizations to reduce greenhouse gas (GHG) emissions are considered to be “science based” if they are in line with what the latest climate science says is necessary to meet the goals of the Paris Agreement. In the United States, the Biden Administration has developed GHG reduction goals which include reducing economy-wide net greenhouse gas (GHG) emissions 50-52% by 2030 from 2005 levels and achieving net zero emissions economy-wide by no later than 2050.

With the large amounts of sustainable biomass used for energy generation, the forest products industry has unique opportunities and constraints associated with developing an achievable strategy for attaining net zero. This NCASI white paper provides an overview of decarbonization technologies available that could enable achievement of net zero, along with calculations of the resources and costs that may be required to reduce and/or offset the current US forest products industry GHG profile.

2.0 Background on the US Forest Products Sector

The US pulp and paper industry has made significant reductions in greenhouse gas emissions.

Since 1990, the industry has reduced Scope 1 and Scope 2 emissions by 50% on both a mass and intensity basis (NCASI 2021a). GHG reductions for the industry have been driven by reductions in facility energy intensity over time, fuel switching from more GHG intense fuels to less GHG intense fuels, and, since 2000, production reductions within the sector. Direct (Scope 1) emissions for the sector were 38.7 million metric tons CO₂e in 2018. Approximately 10.5 million metric tons of direct emissions were process-related (from industry lime kilns, landfills, and wastewater treatment (WWT) systems), and the remainder of direct emissions were from combustion sources for energy generation. Indirect (Scope 2) emissions for the sector were 19 million metric tons CO₂e in 2018. The US pulp and paper sector’s 2018

² <https://www.ipcc.ch/sr15/>

greenhouse gas manufacturing profile is provided in Table 1. Equivalent information on the US wood products sector’s 2018 greenhouse gas manufacturing profile is provided in Table 2.

Table 1. The US Pulp and Paper Sector’s Manufacturing-Related Greenhouse Gas Profile

Category	2018 Emissions (Million mt CO ₂ e)
Scope 1	38.7
Combustion related	28.2
Lime Kilns (fossil)	5.8
Industry owned and operated landfills	4.5
Industry owned and operated WWT systems	0.2
Scope 2*	19
Biogenic emissions	115
Spent liquor solids	79
Other biomass residuals	28
Lime kilns (biomass portion)	8
Total	172.2

* Only includes GHG emissions associated with purchased electricity. Emissions associated with purchased steam are relatively small.

Table 2. US Wood Products Sector’s Manufacturing-Related Greenhouse Gas Profile

Category	2018 Emissions (Million mt CO ₂ e)
Scope 1	5.1
Scope 2*	9.0
Biogenic emissions	22.0
Total	36.1

* Only includes GHG emissions associated with purchased electricity.

The forest products sector uses sustainable biomass energy for most of its energy needs.

The forest products sector is unique among industrial sectors in that most energy requirements for the sector are derived from biomass energy sources. In 2018, 63% of fenceline energy needs for the pulp and paper sector and 60% of fenceline energy needs for the wood products sector were derived from biomass fuels. Biogenic CO₂ emissions for the US forest products sector were 137 million metric tons of CO₂e (115 million metric tons of CO₂e from the pulp and paper sector and 22 million metric tons of CO₂e from the wood products sector) in 2018 and represent a significant opportunity for the sector to become a net negative emitter of GHG emissions if these biogenic emissions are captured with carbon capture technologies.

Biomass used by the forest products sector for energy generation is primarily in the form of biomass residuals and biomass by-products and cannot be replaced by alternative energy sources without significant negative GHG emission impacts.

Spent liquor solids

When pulp is produced from wood chips using a chemical pulp process, wood fibers used to make paper and paperboard products are separated from the wood chips in a digester. The residual digester liquid is called spent pulping liquor, which contains the dissolved portion of the wood not needed for pulp and paper making as well as the spent cooking chemicals. Spent pulping liquor is concentrated to be used as fuel in a recovery furnace (also called a recovery boiler), which is the central component of the mill's recovery system. This system recovers pulping chemicals and energy from the spent pulping liquor. The most common form of spent pulping liquor is black liquor produced by the kraft process. The kraft recovery process is highly resource efficient. Typical chemical recovery efficiencies (a measure of the amount of pulping chemicals recovered and reused for pulping) are approximately 97% (Tran and Vakkilainen 2008), and well operating bleached kraft mills with low liquor losses to sewer can have chemical recovery efficiencies approaching 99% (NCASI 2016).

Due to the importance of the kraft process to the pulp and paper sector³, NCASI undertook a life cycle-based assessment of the benefits of using black liquor solids (Gaudreault et al. 2012; NCASI 2011). The results from that study include:

- The GHG emissions and non-renewable energy consumption for a system using black liquor solids in the kraft recovery system are approximately 90% lower than those for a comparable fossil fuel-based system.
- Use of black liquor solids in the kraft recovery system avoids approximately 140 kg CO₂ eq. per GJ of energy output from the system.
- Applying these results to the production of kraft pulp in the US, the avoided emissions are approximately 100 million metric tons of CO₂ equivalents per year. These avoided emissions are greater than the total Scope 1 + Scope 2 emissions from the US pulp and paper industry.
- The GHG benefits occur without affecting the amount of wood harvested or the amount of chemical pulp produced.
- The results do not depend on the accounting method for biogenic carbon.
- The findings are valid across a range of assumptions about the displaced fossil fuel, the GHG-intensity of the grid and the fossil fuels used in the lime kiln.
- Even at facilities without combined heat and power cogeneration systems, 80 to 90% of the GHG benefits are retained.

Biomass residuals

The use of manufacturing and forest biomass residuals in power boilers is a long-established practice within the forest products industry. Combustion of biomass residuals other than spent liquor solids for energy generation represented 304 trillion Btu of energy in 2018 for the US pulp and paper sector⁴. For the US wood products sector, combustion of biomass residuals represented 233 trillion Btu of energy in 2018.

³ Approximately 90% of wood pulp (pulp derived from chemical pulping, semi-chemical, and mechanical pulping) produced in the United States is from the kraft process.

⁴ <https://www.eia.gov/consumption/manufacturing/data/2018/>

The forest products sector is a leader in the utilization of combined heat and power.

Combined heat and power (CHP) is an energy efficient mode of steam and electricity generation. The US forest products industry produced 32% of all the CHP generated by manufacturing industries in 2018⁵. Over 40 billion kWh of electricity was co-generated by the US forest products industry in 2018, representing 95% of all onsite electricity generated by the sector⁶. Pulp and paper and wood product facilities utilize predominantly biomass-based CHP to generate steam and electricity with very low GHG emissions. The US pulp and paper sector avoids over 12 million metric tons CO₂e annually by using CHP compared to the separate generation of steam and electricity (NCASI 2021b). The forest products sector sold 6,449 million kWh in 2018, which helps contribute to greening of the US electrical grid. Given that electricity is being generated at the point of use, forest product CHP systems also contribute to overall electrical grid resiliency.

The pulp and paper sector has high thermal loads.

In chemical pulp and paper mills, thermal demand (in the form of steam) represents 75-90% of total fence-line energy needs. Because of the large thermal loads and the use of primarily biomass residuals and biomass by-products (black liquor) for energy generation, approaches such as electrification of process heat may not be economically feasible or ecologically desirable.

The forest products sector produces a variety of products using a variety of different processes.

The US pulp and paper sector is a diverse industrial sector producing products such as packaging material, tissue and towel products, printing and writing paper, newsprint, and specialty papers. These products are made using a variety of different processes based on chemical, mechanical, and recycled pulp production. The US wood products sector produces a variety of products such as lumber, plywood, veneer, particleboard, oriented strand board, hardboard, fiberboard, medium density fiberboard, laminated strand lumber, laminated veneer lumber, wood I-joists, and glue-laminated beams. These products are made from a variety of different wood types. Because of the diversity of products and processes, adoption of transformational technologies is a particular challenge for the forest products sector.

3.0 The Pillars of Decarbonization for the US Forest Products Sector

The US Department of Energy (DOE) has published an industrial decarbonization roadmap outlining decarbonization approaches for the iron and steel sector, chemical manufacturing, food and beverage manufacturing, petroleum refining, and cement manufacture (DOE 2022). Within the DOE document, the following pillars of decarbonization were highlighted:

- Energy efficiency including combined heat and power utilization
- Manufacturing of low-carbon fuels, feedstocks, and energy sources
- Carbon capture, utilization, and storage
- Electrification of heat

⁵ https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

⁶ https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

This white paper follows the DOE pillars of decarbonization approach in the context of the forest products sector. It is important to recognize that the decarbonization pillars cannot be applied uniformly across the entire forest products sector. Table 3 shows the GHG emission distribution by major mill sub-sector for the US pulp and paper sector. Technologies such as bioenergy carbon capture are only applicable to the chemical pulp subsector. Electrification of heat approaches may be more applicable to the non-integrated and recycle and mechanical pulp sub-sectors since those sub-sectors do not use low cost, low GHG biomass fuels to meet energy needs. Progress toward greening the electrical grid will benefit all major sub-sectors approximately equally. Table 4 shows GHG emission distribution by major wood product production type. Biogenic emissions in the wood products sector (lumber, structural panels, non-structural panels) represent approximately two-thirds of total emissions. Panel plants tend to have higher Scope 1 emission contributions compared to lumber mills.

Table 3. Greenhouse Gas Emission Distribution by Major Pulp and Paper Mill Type

Mill Type	Biogenic Emissions (mt CO ₂ /year)	Purchased Electricity (mt CO ₂ e)	Scope 1 (mt CO ₂ e)
Chemical	99%	39%	63%
Non-integrated	0.4%	35%	19%
Recycle and mechanical	0.6%	26%	17%

Table 4. Greenhouse Gas Emission Distribution by Major Wood Product Facility Type

Sub-sector	Biogenic Emissions (% of total)	Net Electricity (% of total)	Scope 1 Emissions (% of total)
Lumber	78%	20%	1%
Structural panels	72%	21%	6%
Non-structural panels	64%	25%	11%

4.0 Energy Efficiency Including Combined Heat and Power Utilization

Energy efficiency improvements for the pulp and paper sector have been the subject of many papers, studies, and analyses. Some examples of compilations of energy efficiency approaches for the pulp and paper sector include Francis et al. 2002, Kramer et al. 2009, Miller et al. 2015, and Hubbe 2021. In general, energy efficiency improvements are the lowest cost approach to decarbonization within the pulp and paper sector (the less energy required to make a product generally translates to less GHGs emitted from making the product). For a facility that has not undertaken a previous energy audit, a typical mill energy audit may identify energy reduction possibilities of 20% at a facility, with a quarter to half of the identified projects requiring no capital expenditures (Reese et al. 2020). This white paper does not focus on energy efficiency improvements but does outline trends for energy intensity for the sector over time. The overall energy intensity of the US pulp and paper sector has decreased over time as mills have implemented energy efficiency improvements and installed more energy efficient equipment. Figure 1 shows trends in total fence-line energy intensity over time from 1972 to 2018. There has been a 31% reduction in total fence-line energy intensity in the US pulp and paper sector since 1972.

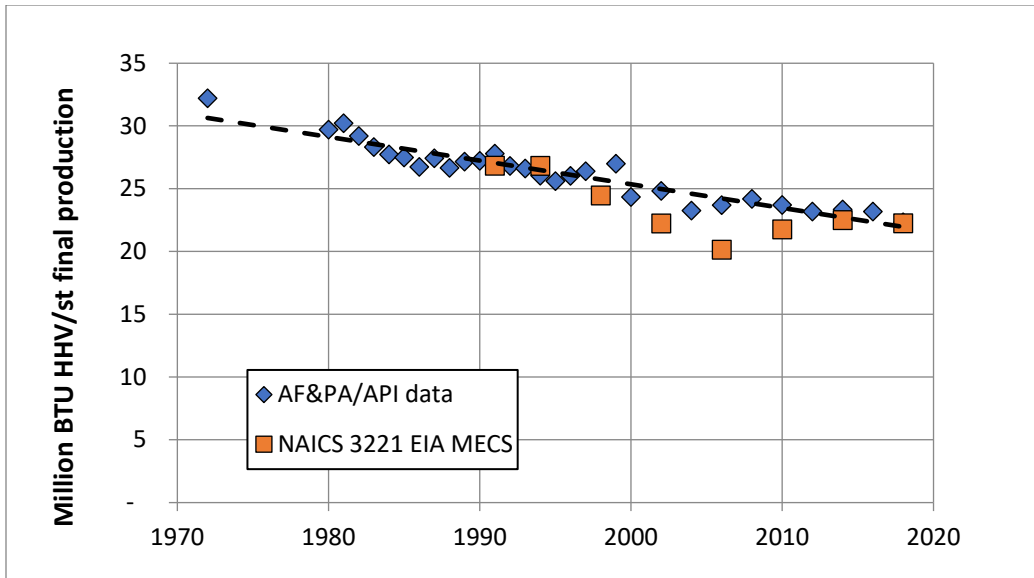


Figure 1. Changes in Total Fenceline Energy Intensity Over Time from AF&PA/API⁷ and EIA MECS⁸ Data for the US Pulp and Paper Sector (NCASI 2021a)

Figure 2 shows total fenceline energy intensity over time divided between fossil fuels, net purchased electricity and steam, and biomass and other renewables. The trend shows that the portion of fenceline energy needs associated with biomass and hydroelectricity has increased over time.

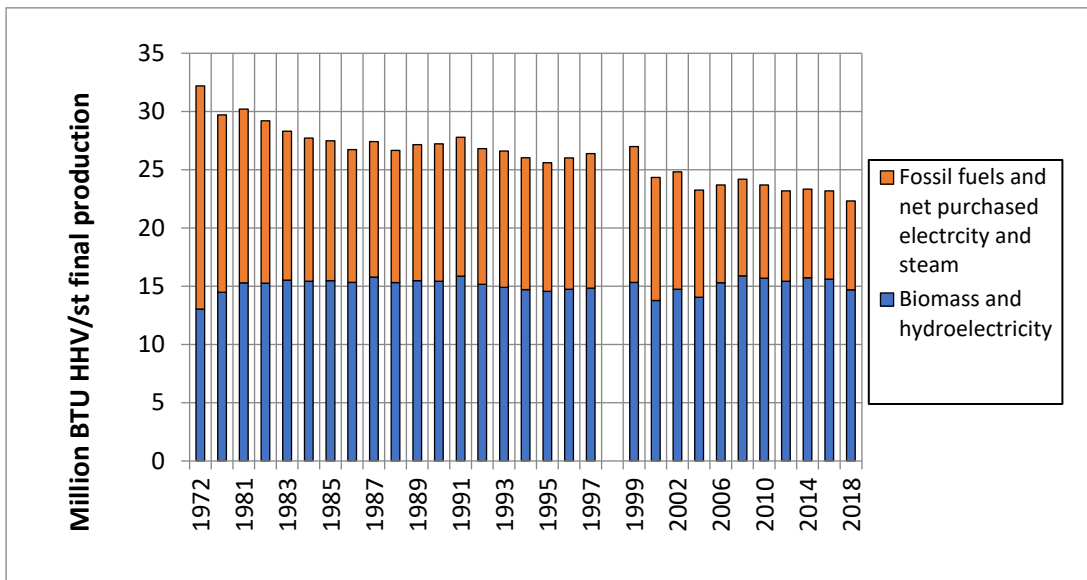


Figure 2. Changes in Total Fenceline Energy Intensity Over Time and Changes in Biomass and Fossil Energy Share from AF&PA/API data (NCASI 2021a)

⁷ The American Forest and Paper Association (AF&PA) and its predecessor, the American Paper Institute (API)

⁸ US Energy Information Administration (EIA) manufacturing energy consumption survey (MECS)

4.1 Combined Heat and Power

The forest products industry is a leader in the use of combined heat and power, which is an energy efficient mode of steam and electricity generation from the same fuel source. Several documents recognize the energy efficiency and resiliency benefits of industrial (including forest products) combined heat and power (US EPA 2017; NREL 2017; DGA and Institute of Industrial Productivity 2015). The broad advantages of CHP include:

- The simultaneous production of useful thermal and electrical energy, which is a more efficient generation mode than the separate generation of steam and electricity.
- Installation of CHP units at the point of energy use to avoid transmission and distribution losses that would occur with purchased power.
- Reduced dependency on the grid, particularly during power disruptions or outages.

The US forest products industry currently has 12.7 GW of installed CHP capacity (Table 5).

Table 5. US Forest Products Industry Installed CHP Capacity⁹

Sector	Installed CHP Capacity (GW)
Pulp & Paper	11.8
Wood Products	0.9
Forest Products	12.7

The US forest products industry produced 32% of all the CHP generated by manufacturing industries in 2018¹⁰. Over 40 billion kWh of electricity were generated through CHP by the US forest products industry in 2018, representing 95% of all onsite electricity generated by the sector (see Table 6). The US pulp and paper sector avoids over 12 million mt CO₂e annually by using CHP compared to the separate generation of steam and electricity (NCASI 2021b). The forest product sector sells 6.5 billion kWh of electricity annually, predominately from biomass-based CHP systems that have low GHG emissions. Table 6 shows the US forest products industry electricity generation profile for 2018. Electricity sales within the pulp and paper sector represented 13% of total sector electricity generation in 2018. Electricity sales within the wood products sector represented 59% of total sector electricity generation in 2018.

Table 6. The US Forest Products Industry Electricity Generation Profile

Sector	Cogenerated Electricity ¹ (million kWh)	Total Onsite Electricity Generation ² (million kWh)	Percentage of Onsite Electricity that is Cogenerated	Sales ² (million kWh)
Pulp and Paper	38,663	40,518	95%	5,372
Wood Products	1,735	1,840	94%	1,077
Forest Products	40,398	42,358	95%	6,449

¹ https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

² https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_1.pdf

⁹ <https://doe.icfwebservices.com/downloads/chp>

¹⁰ https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

5.0 Low-Carbon Fuels, Feedstocks, and Energy Sources

The onsite energy mix for the US pulp and paper industry over time, based on EIA MECS data, is shown in Figure 3. The same mix, based on AF&PA/API data, is shown in Figure 4. In 1991, coal and other fossil fuels (primarily residual fuel oil) represented 13% and 7% of the onsite energy mix, respectively. In 2018, the coal contribution had decreased to 3%, and the other fossil fuels' contribution had decreased to 1%. Between 1991 and 2018, the natural gas energy contribution increased from 20 to 26%, and the biomass energy contribution increased from 53 to 63%. Net purchased electricity remained essentially constant between 1991 and 2018, at 7% of the energy mix. The US pulp and paper industry has achieved substantial GHG reductions¹¹ partly through installation of biomass power boilers and the switching away from more carbon-intensive fuels like coal.

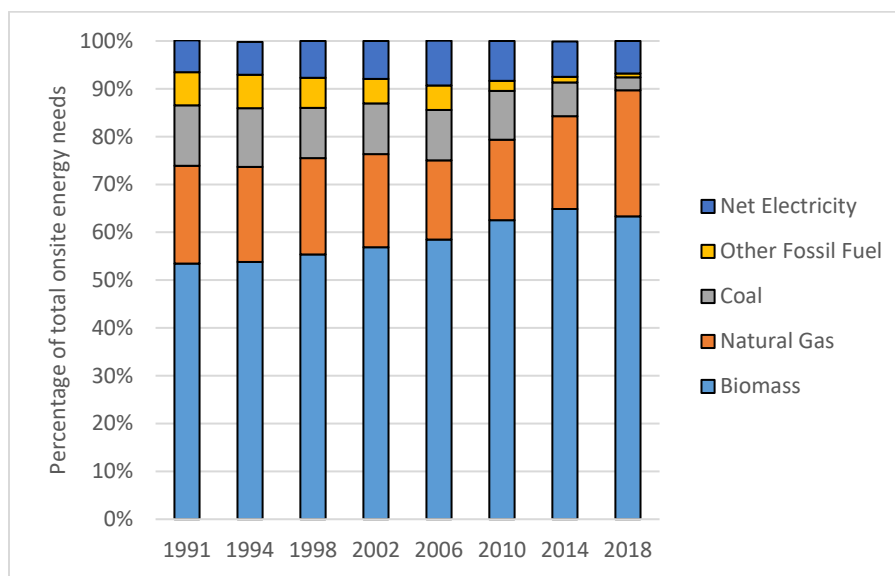


Figure 3. Onsite Energy Mix Over Time for the US Pulp and Paper Industry Based on EIA MECS Data (NCASI 2021a)

¹¹ <https://www.afandpa.org/sites/default/files/2022-02/BPBP2020SustainabilityGoalsAchievementsSummary-2-2-22.pdf>

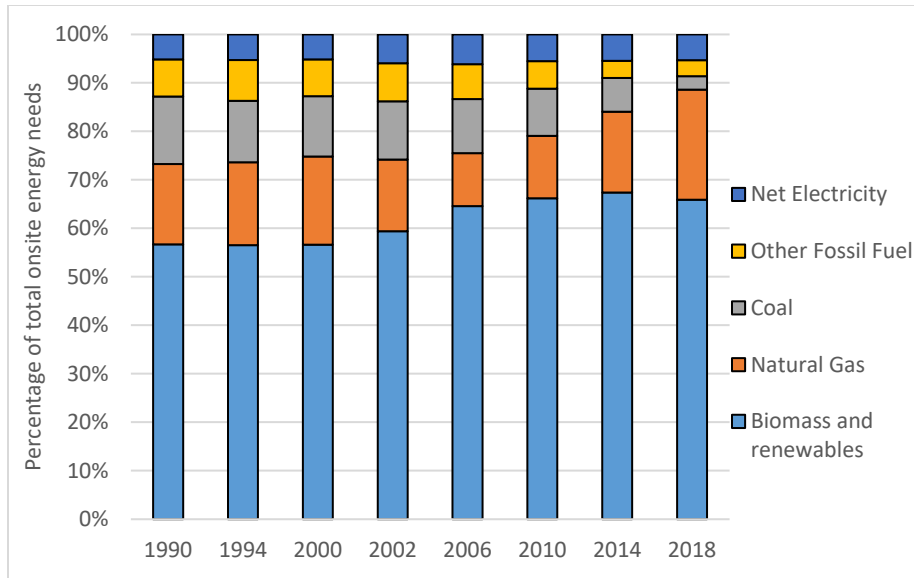


Figure 4. Onsite Energy Mix Over Time for the US Pulp and Paper Industry Based on AF&PA/API Data (NCASI 2021a)

The onsite energy mix for the US wood products sector over time, based on EIA MECS data, is shown in Figure 5. The biomass fuel contribution for the wood products sector has averaged 63% of total fuel mix between the period of 1991-2018.

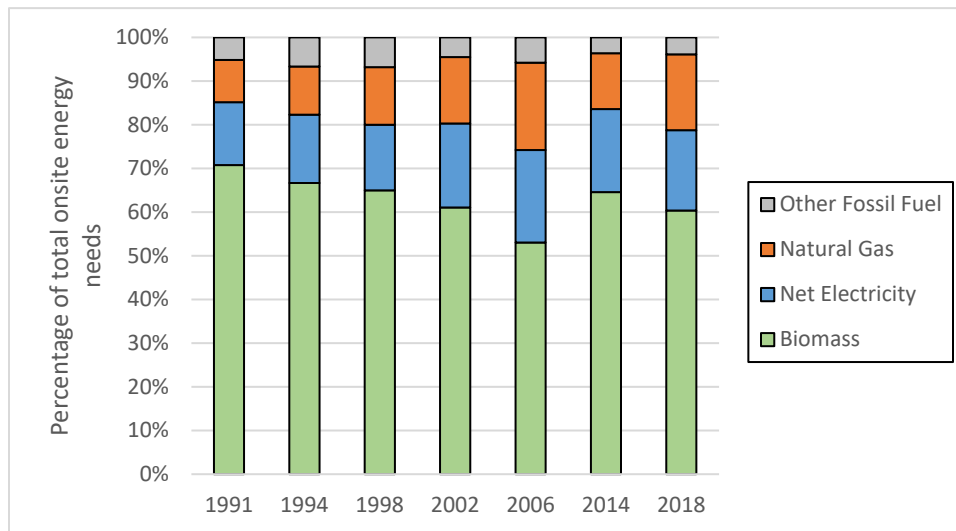


Figure 5. Onsite Energy Mix Over Time for the US Wood Products Sector Based on EIA MECS Data

Switching from more GHG intense fuels, such as coal and residual fuel oil, to less or very low GHG intense fuels, such as natural gas and biomass, has contributed to GHG reductions on both an intensity and absolute basis for the US pulp and paper industry. Since 1990, the industry has reduced Scope 1 and Scope 2 emissions by 50% on both mass and intensity bases (NCASI 2021a). GHG emissions from natural gas per unit of energy are approximately half that of coal, so increases in natural gas usage, if offset by

similar or greater reductions in higher GHG intensity fuels such as coal and residual fuel oil, lead to a reduction in GHG intensity.

5.1 Biomass Power Boilers

The utilization of manufacturing and forest biomass residuals in power boilers, often called hog fuel boilers, is a long-established practice within the forest products industry. The combustion of biomass residuals other than spent liquor solids¹² for energy generation at pulp and paper mills represented 304 trillion Btu of fuel energy in 2018¹³. For the US wood products sector, combustion of biomass residuals represented 233 trillion Btu of energy in 2018. A summary of biomass residual utilization in biomass power boilers is provided in Table 7.

Table 7. *Biomass residual utilization in power boilers in the US forest products sector in 2018*

Sector	Biomass Residuals other than Spent Liquor Solids (trillion Btu HHV)
Pulp & Paper	304
Wood Products	233
Forest Products	537

5.2 Biomass Utilization in Lime Kilns

Rotary lime kilns are present in kraft chemical pulp mills and are part of the kraft chemical recovery system. Lime kilns are large, countercurrent reactor systems that convert calcium carbonate (CaCO₃) to calcium oxide (CaO). The lime calcination reaction is endothermic and requires high temperatures of above 1100°C at the hot end of the kiln. Fossil fuels such as natural gas, residual fuel oil, and petcoke are the most common fuel sources for heating, drying, and calcining lime. The lime kiln heat rate is the most prevalent measure of energy efficiency in lime kilns and is expressed in GJ/metric ton (mt) CaO (MMBtu/short ton (st) CaO) or GJ/mt lime kiln discharge (MMBtu/st lime kiln discharge¹⁴).

NCASI periodically synthesizes data on energy use in pulp and paper lime kilns as part of its efforts to collect combustion source information from US pulp and paper mills. Previous survey efforts characterized lime kiln energy use from 2005, 2010, and most recently from 2018. A 1982 survey of energy consumption in lime kilns operating within Canada collected data from 29 mills operating 37 lime kilns (Simonsen and Azarniouch 1987). Average fuel consumption from that study was 11.1 GJ/mt of kiln discharge¹⁴ (9.6 million Btu/st of kiln discharge) or 13.0 GJ/mt of active CaO (11.3 million Btu/st of active

¹² Spent liquor solids are combusted in kraft recovery furnaces as fuel. In 2018, 919 trillion Btu of fuel energy were utilized in kraft recovery furnaces in the US pulp and paper sector.

¹³ <https://www.eia.gov/consumption/manufacturing/data/2018/>

¹⁴ Lime kiln discharge consists of a mixture of CaO and CaCO₃ and minor amounts of other inorganics (usually classified as inerts). Incomplete conversion from CaCO₃ to CaO and the presence of inerts is expressed through lime availability, i.e., 90% lime availability means 90% of the lime discharge is present as CaO on a weight basis. Lime availability normally ranges from 85-95 weight % but can be substantially lower in mills that are experiencing lime mud washing issues or inerts accumulation in the lime cycle.

CaO), assuming a lime availability of 85%. More recently, energy use data in Canadian pulp and paper mills were collected by Paprican (now FPInnovations) and published in an NRCan document (2008). This survey effort collected data from 51 mills, 49 operating in Canada and two in the United States. Average lime kiln energy use from that survey was 2.19 GJ HHV/oven dry metric ton (ODt) of unbleached pulp¹⁵ (NRCan 2008). Francey et al. (2011) published information from a global survey on lime kiln performance and practices. This survey collected information from 59 pulp mills operating 67 lime kilns. The pulp mills were located in North America, South America, the Nordic countries, and New Zealand, with survey information reflecting operations in 2008. Heat rates ranged from 5-11 GJ/mt CaO (4.2-9.1 MMBtu/st CaO) (Francey et al. 2011). Adams (2007) provided an overview of lime kiln operations and energy savings approaches and reported typical lime kiln heat rates in the 5-9 MMBtu/ton CaO range. A comparison of heat rate statistics from previous kiln energy consumption studies and NCASI survey data is provided in Table 8. Figure 6 shows the distribution of heat rate information from NCASI surveys, and Figure 7 shows the distribution of heat rate information from NCASI surveys and the information from Francey et al. (2011), which is more international in context.

Energy efficiency measures at pulp and paper lime kilns target minimizing energy losses associated with heat losses through the kiln shell, in the hot lime product, and associated with the exiting flue gas and dust. Lime kiln energy efficiency measures implemented at facilities include increasing lime mud dry solids by more efficient dewatering or lime mud drying, installation of more effective insulating refractory such as double refractories, addition of product satellite coolers, improved chain systems, installation of automatic process control systems to minimize excess air, and fuel switching. Adams (2007) provides an overview of possible improvements to lime kiln heat rates by implementation of some of these energy efficiency measures.

Table 8. Heat Rate (GJ HHV/mt CaO) Statistics for Lime Kiln Operation

	NCASI 2005	NCASI 2010	Simonsen and Azarniouch 1987	NRCan 2008	Francey et al. 2011	Adams 2007
Lime Kiln Count	148	135	32	25	48	
Average	8.2	8.4	13.0	10.3	6.9	
Standard deviation	2.2	2.4	2.4	1.9		
Minimum	3.2	2.5	9.4	6.8	4.8	5.8
Maximum	18.2	19.3	17.8	14.8	10.6	10.5
Median	8.1	8.2	12.8	10.1		

¹⁵ The lime production in the recovery cycle is mill specific and can range from 200 to over 300 kg of lime product per oven-dry metric ton of unbleached pulp (Hough 1985; Grace and Malcolm 1989; Gullichsen and Paulapuro 1999). In the absence of mill-specific information, a value of 250 kg of lime product per oven-dry metric ton of unbleached pulp can be used to convert lime kiln heat rate information from a GJ/mt kiln discharge or GJ/mt of active CaO basis to a GJ/ODt basis.

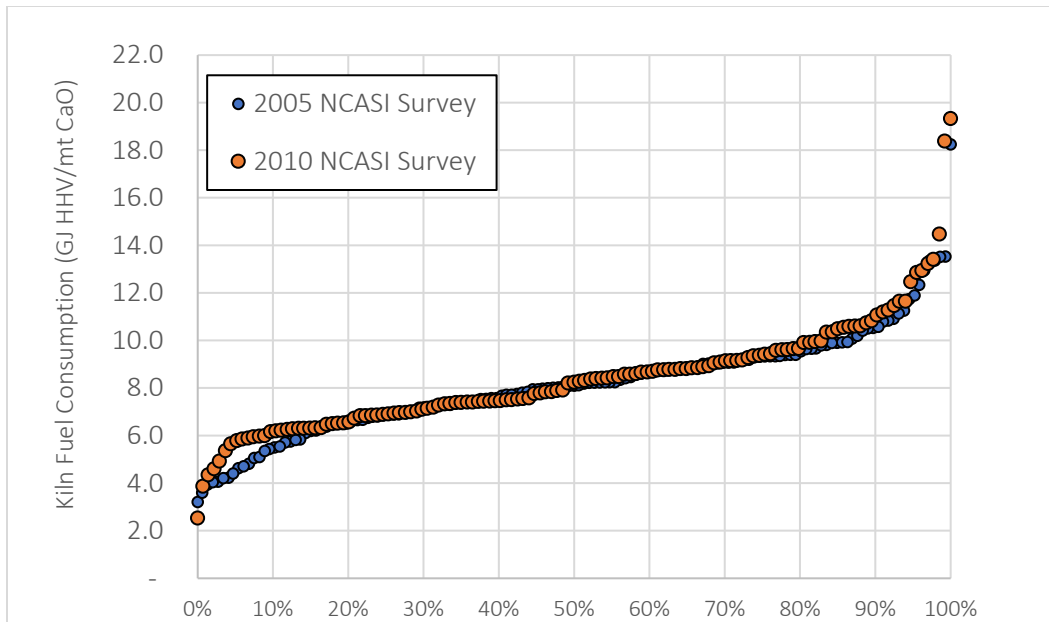


Figure 6. Distribution of Lime Kiln Fuel Consumption at US Mills

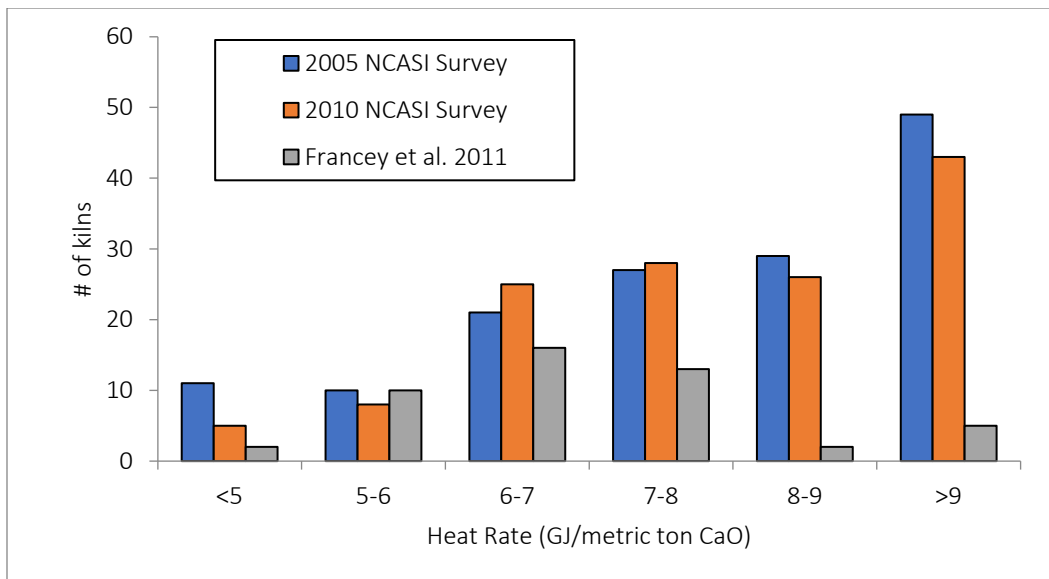


Figure 7. Distribution of Lime Kiln Fuel Consumption from NCASI and International Surveys

Carbon dioxide emissions from pulp and paper lime kilns differ from CO₂ emissions from the cement industry because approximately 61% (9 million mt CO₂e) of annual CO₂ kiln stack emissions from the pulp and paper sector are biomass-based (Miner and Upton 2002). The remaining 39% (5.8 million mt CO₂e) of annual CO₂ kiln stack emissions are fossil based (US EPA GHGRP¹⁶). For the US pulp and paper

¹⁶ <https://www.epa.gov/ghgreporting/data-sets>

sector, the 5.8 million mt CO₂e emissions from US pulp and paper lime kilns represent approximately 21% of total natural gas and residual fuel oil GHG emissions from the sector and approximately 15% of total direct emissions for the sector (see Table 1). Table 9 provides the fuel distribution on an energy percentage basis for US lime kilns. Using the information in Table 8, Table 9, and a typical conversion to unbleached pulp, an average GHG emission factor for US lime kilns is 105 kg CO₂e/mt unbleached pulp based upon 2010 data from 135 US kilns. This value is similar to the median reported by Taillon et al. (2018) (100 kg CO₂/metric ton).

Table 9. Fuel Distribution on an Energy Basis for US Lime Kilns

Fuel	Energy Percentages (%)
Natural gas	64.7
Residual fuel oil	34.3
Petcoke	1.0

Even though there are several wood biofuel possibilities to replace fossil fuels in the lime kiln, e.g., directly fired wood residues (bark, sawdust), pyrolysis oil, precipitated lignin, and gasified wood residues (bark, sawdust) (Francey et al. 2009; Kuparinen and Vakkilainen 2017), the use of gasified biomass residuals to replace fossil fuels within lime kilns appears to be the most promising biomass substitution technology, with several commercial installations at chemical pulp mills undertaken by Andritz and Valmet. The basic schematic of biomass gasification systems for lime kilns is provided in Figure 8. Dried biomass is fed to a gasification unit that is based upon fluidized bed technology. A synthesis gas (“syngas”) is produced from the gasification unit that is used as the combustion source within the lime kiln.

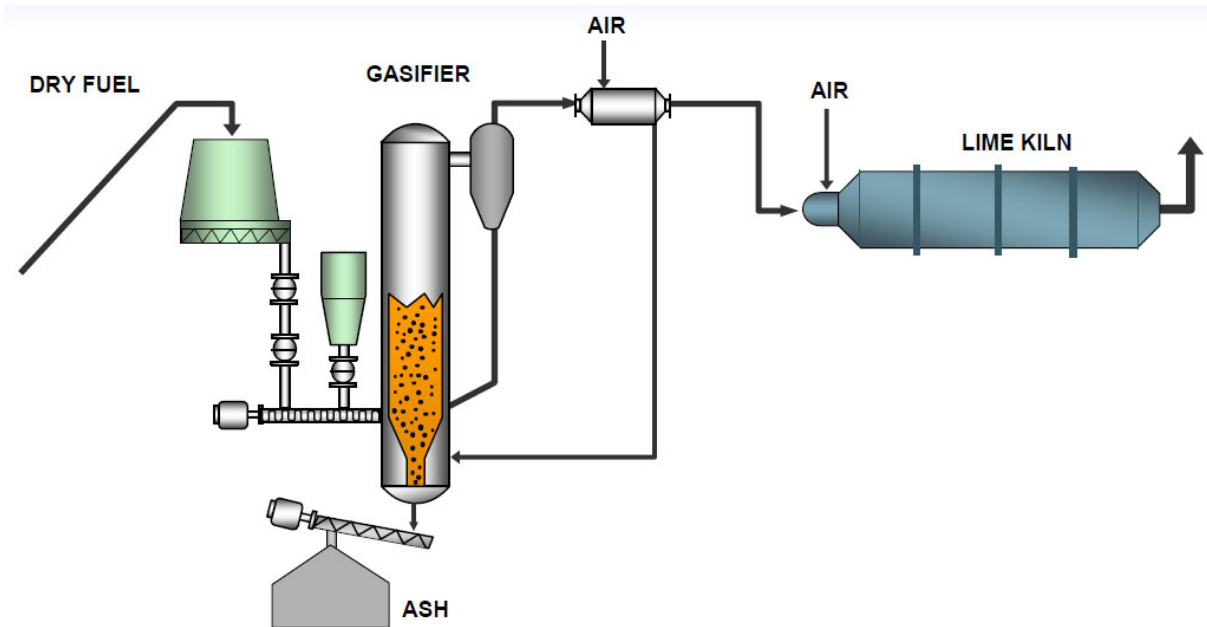


Figure 8. Schematic of a Pulp Mill Biomass Gasification System (Patel and Salo 2007)

Biomass pretreatment is required for biomass gasification and includes removal of sand and metals, drying, chipping, and grinding to achieve the required moisture content and homogeneity of biomass (Kuparinen and Vakkilainen 2017). Hot water, low pressure steam, or flue gas are used for the drying step (see examples in Table 11). Electricity for the biomass grinding and belt drying is in the range of 190 kWh/mt, and the electricity consumption of the gasifier air fans is approximately 1.1% of the thermal power of the gasifier (Kuparinen and Vakkilainen 2017). Biomass moisture should be as low as possible (< 5 - 8%) to improve energy efficiency and minimize flue gas volume (Jensen 2021). Bark is preferred as the heat source because of its higher heating value compared to other biomass residuals (Jansen 2021). Circulating fluidized bed (CFB) gasifiers are rated up to 140 MW_{thermal} from Valmet and Andritz. Make-up lime requirements typically increase with biomass gasification units to manage accumulation of non-process elements (NPE), which are present in the biomass (Jensen 2021; Kuparinen and Vakkilainen 2017). Lime make-up increases of approximately 2 kg/ADt may be expected (Kuparinen and Vakkilainen 2017).

Syngas from biomass gasification units have heating values of 3.5 – 11.5 MJ HHV/kg, depending upon moisture content of the incoming biomass, biomass source, and the use of O₂ or combustion air (Francey et al. 2009; Mackie et al. 2008; Jensen 2021). The heating value of natural gas (53 MJ HHV/kg) and fuel oil (43 MJ HHV/kg), the most typical fossil fuels used in pulp and paper lime kilns in the United States, are comparatively much higher. The lower fuel heating values of syngas lead to different heat transfer profiles within the kiln and higher gas flow rates through the kiln, which negatively impact, i.e., increase, kiln heat rates and lime availability (Yuan et al. 2010). Table 10 provides a summary of heating values of fossil fuels used in lime kilns and biomass-derived syngas used in lime kilns.

Table 10. Heating Value Comparison of Fossil Fuels and Gasified Wood Residuals

Fuel	Higher Heating Value (MJ/kg)	Source
Natural gas	53.2	Francey et al. 2009
Fuel oil	43.1	Francey et al. 2009
Pulverized petcoke	34.8	Golebiowski and Weakly 2007
Syngas from Valmet CFB gasifiers	2.8 -6.6	Jensen 2021
Syngas from wood residues ¹	3.5 – 11.5	Francey et al. 2009
Raw syngas ²	3.73	Mackie et al. 2008
Upgraded syngas ³	5.96	Mackie et al. 2008
Cleaned syngas ⁴	4.10	Mackie et al. 2008
Methanated syngas ⁵	11.18	Mackie et al. 2008

¹ Dependent upon wood residual type, moisture content, and the use of O₂ or air for gasification

² Wet fuel, air and flue gas, with tar

³ Dry fuel, air and steam, with tar

⁴ Dry fuel, air and steam, without tar

⁵ O₂, steam, no inerts, without tar

Biomass gasification for lime kilns is Technology Readiness Level (TRL)¹⁷ 9 with several installations by Valmet and Andritz at pulp and paper facilities. Valmet has installed seven gasification units at five different mills as of 2021 (Jensen 2021). Andritz has installed at least four gasification units at four different mills (Taillon et al. 2018; Andritz press release)¹⁸. Table 11 shows current lime kiln biomass gasification installations at pulp and paper mills. There are currently no lime kiln biomass gasification installations in North America.

Table 11. Lime Kiln Biomass Gasification Installations at Pulp and Paper Mills

Company	Mill	Startup Year	Number of installations	Gasifier Size (MW _{thermal})	Lime Throughput (tpd)	Vendor
MetsäFibre	Kemi, Finland	2022	1	100	1400	Valmet
Bracell	STAR, Brazil	2021	2	87	1300	Valmet
Chenming	Huanggang, China	2018	1	50	900	Valmet
MetsäFibre	Äänekoski	2017	1	87	1200	Valmet
APP	OKI, Indonesia ¹	2017	2	110	1250	Valmet
Klabin	Puma Unit Ortigueira/PR Brazil	2022	1	51	Not available	Andritz
MetsäFibre	Joutseno ²	2012	1	48	600	Andritz
Chenming	Zhanjiang ³	2014	1	65	800	Andritz
Chenming	Shouguang Meilun	2018	1	80	Not available	Andritz
Eska Graphic Board	Netherlands ⁴	2016	1	12	N/A	Leroux & Lotz Technologies (LLT)

¹ Fuel: Acacia bark and wood

² Dryer heat source: mill filtrates and low-pressure (LP) steam; Fuel: bark (pine, spruce, birch) from debarking replacing natural gas

³ Dryer heat source: condensates, lime kiln flue gas, LP steam; Fuel: Eucalyptus bark and chip screening fines replacing heavy fuel oil

⁴ Fuel: recycle mill rejects replacing the use of liquefied petroleum gas (LPG)

Gasification systems with capacities between 25-110 MW_{thermal} (corresponding to 300-1200 tpd lime) offer attractive payback (Taillon et al. 2018). Figure 9 shows the strong relationship between gasifier size and lime throughput in metric tons per day, with the capacity of gasification units for lime kilns ranging from ~50 to 110 MW.

¹⁷ See section “Technology Readiness Level for Carbon Capture” for the definition at ratings of TRLs.

¹⁸ <https://www.andritz.com/newsroom-en/pulp-paper/2022-11-10-klabin-wsa-group>

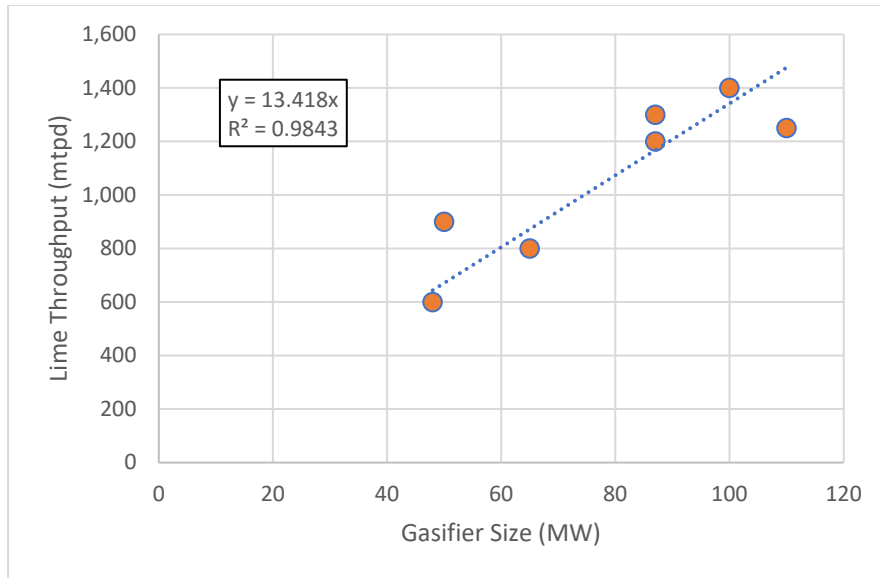


Figure 9. Relationship Between Gasifier Size (MW) and Lime Throughput (metric tons per day)

5.3 Grid Decarbonization

Even though the forest products sector uses sustainable biomass to meet over 60% of its energy needs and self-generates substantial amounts of electricity for driving its processes, it still purchases electricity for process needs. Scope 2 emissions from purchased electricity were approximately 28 million metric tons of CO₂e in 2018, representing about 39% of total Scope 1 and 2 GHG emissions (see Table 12).

Table 12. Purchased Electricity GHG Profile for the US Forest Products Industry

Sector	Purchased Electricity 2018 GHG Emissions (million mt CO ₂ e)
Pulp & Paper	19.0
Wood Products	9.0
Forest Products	28.0

Due to several factors such as the proliferation of state Renewable Portfolio Standards (RPS)¹⁹, state and federal environmental regulations, and market forces, the GHG emission intensity associated with purchased electricity has been decreasing. Figure 10 shows the average US electrical grid GHG emission factor over time based on eGRID data files²⁰. Since 1996, there has been a 41% decrease in the electrical grid emission factor driven by coal power plant retirements, growth in natural gas generation capacity, and rapid growth in renewables as a percentage of grid mix over time.

¹⁹ Renewable Portfolio Standards are regulatory mandates to increase energy production from renewable sources other than fossil fuels and nuclear energy.

²⁰ <https://www.epa.gov/egrid>

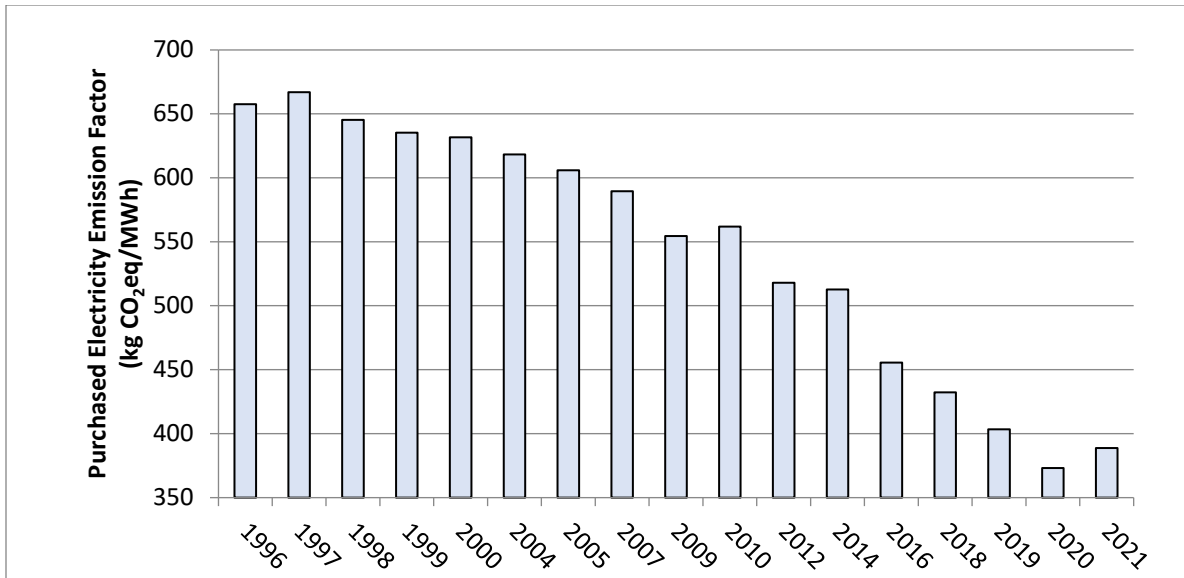


Figure 10. Average US Electrical Grid GHG Emission Factor Over Time Based Upon eGRID

US EPA calculates the amount of renewable energy generation as a portion of the total grid resource mix on a national level and an eGRID subregion level. Figure 11 shows that since 2007, the percent of renewables has increased from approximately 8% to nearly 20% of the total grid mix.

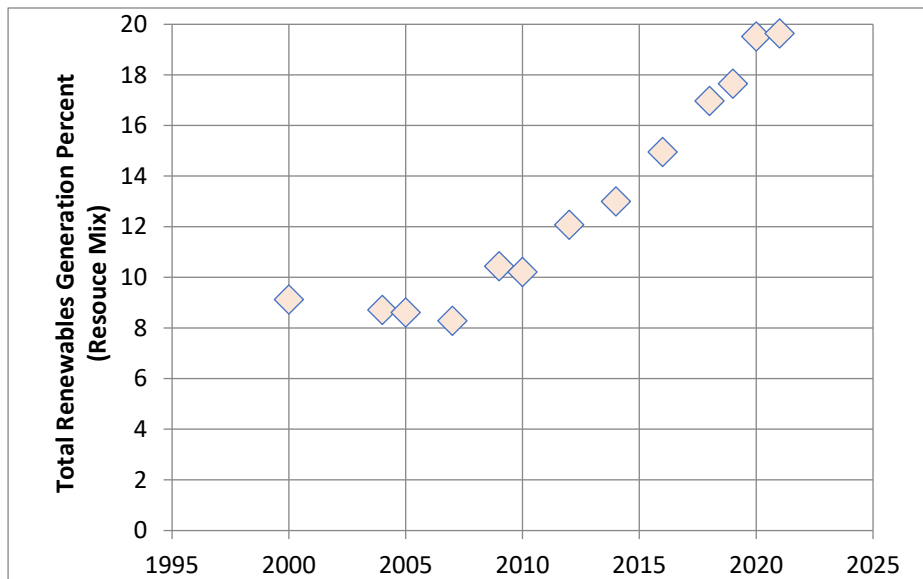


Figure 11. The Percent of Total Renewables Generation Over Time (from US EPA eGRID data files over time)

Figure 12 shows the projections for the US electrical grid based on modeling using US EIA’s Annual Energy Outlook (AEO). The share of renewables²¹ (primarily growth in solar) continues to increase over time and represents 43% of the grid mix in AEO’s Reference Case scenario.

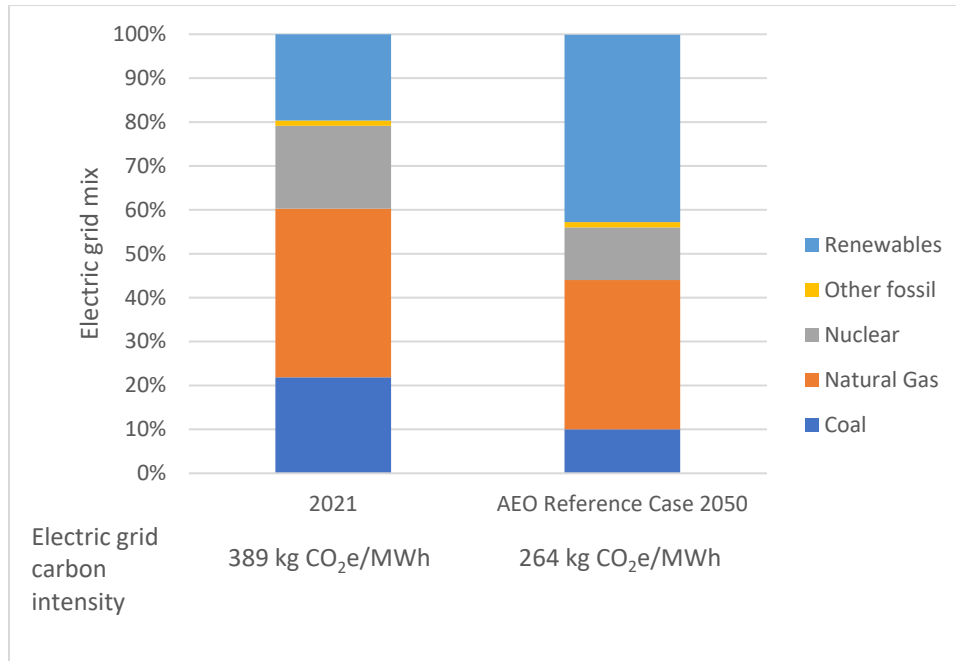


Figure 12. Projections for US Electric Grid Carbon Intensity (based upon eGRID for 2021 and EIA Annual Energy Outlook 2022 for 2050 projections)

The electric grid GHG emission factor for the AEO Reference case is calculated to be 264 kg CO₂e/MWh, a 32% reduction in emission factor compared to the current grid emission factor of 389 kg CO₂e/MWh. US EIA is projecting continued coal, oil and natural gas, and nuclear power plant retirements over the next decade (see Figure 13). Table 13 shows that sustained greening of the electrical grid may result in Scope 2 emission reductions of about 11 million metric tons of CO₂e by 2050 for the entire forest products industry relative to 2018 levels.

Table 13. Projections for the US Forest Products Industry Scope 2 Emissions Due to Continuing Greening of the Electrical Grid

Sector	Purchased Electricity 2018 GHG Emissions (million mt CO ₂ e)	Purchased Electricity 2050 GHG Emissions based upon AEO 2022 (million mt CO ₂ e)
Pulp & Paper	19.0	11.6
Wood Products	9.0	5.5
Forest Products	28.0	17.1

²¹ eGRID classifies solar, wind, biomass, hydro, and geothermal resources as “renewables.”

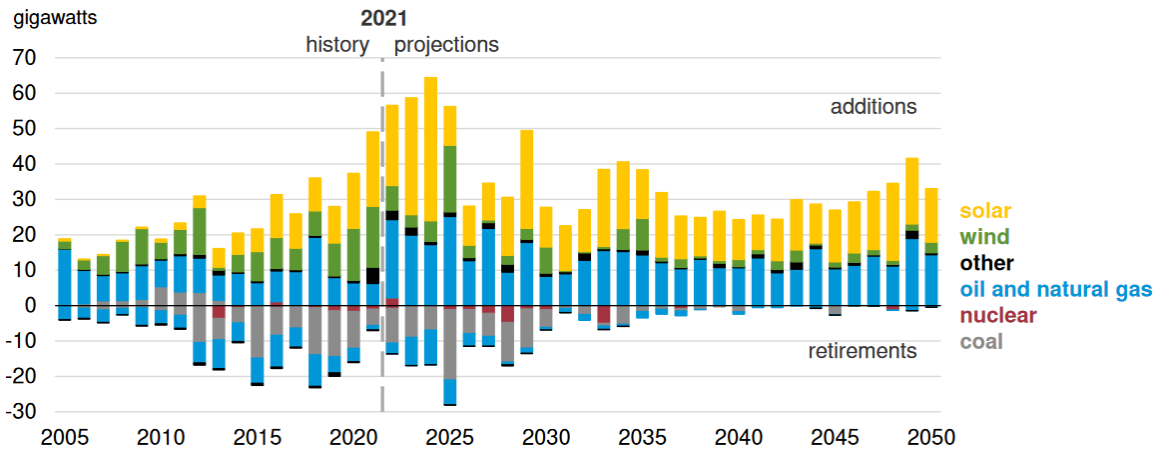


Figure 13. US Grid Additions/Retirements Annual Energy Outlook 2022²²

5.4 Greening of Steam Generators

The pulp and paper sector purchases some steam for operations, and the GHG emissions profile for steam purchases has been decreasing over time as several steam generators have shifted fuels from coal to natural gas. Figure 14 shows average purchased steam emission factors over time within the US (based upon US DOE methodology within EIA-1605²³). For perspective, a 100% natural gas boiler with 80% thermal efficiency would have an emission factor of 62.9 kg CO₂e/GJ steam.

²² <https://www.energy.gov/sites/default/files/2022-11/05%20October%2027%20-%20EIA%20Annual%20Energy%20Outlook%202022.pdf>

²³ Purchased steam emission factors over time are based on the approach used in US DOE Instructions form EIA-1605 (2007) but using time series EIA MECS data. In form EIA-1605, the purchased steam emission factor is based on the weighted average from EIA’s 1998 MECS data on quantities of natural gas, coal, and residual and distillate fuel oils consumed as boiler fuel; carbon coefficients provided in EIA’s Assumptions to the Annual Energy Outlook 2003; and EIA/OIAF efficiency assumptions of 80, 81, and 82% for natural gas, coal, and petroleum boilers, respectively. The steam emission factor value also includes 10% loss during transmission.

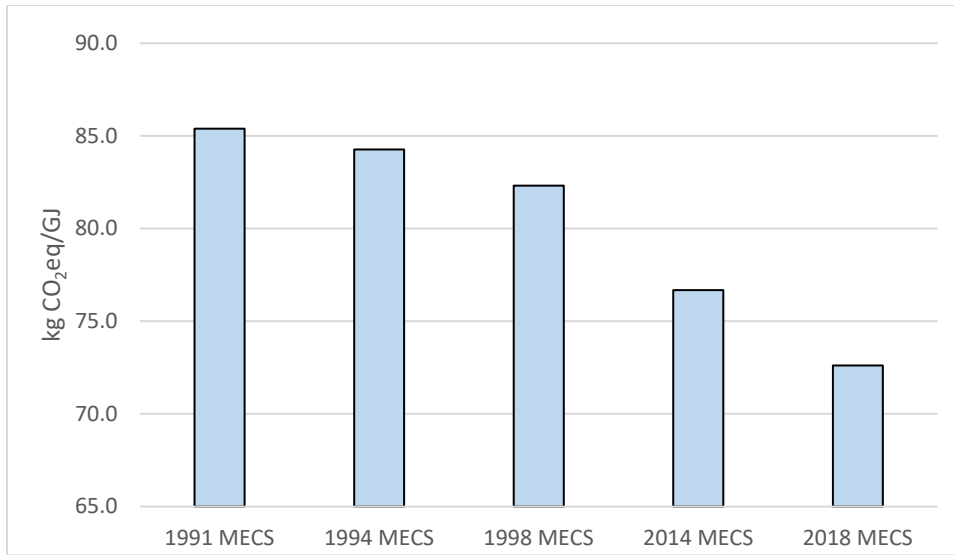


Figure 14. Purchased Steam Emission Factors Over Time

Some mills or wood products facilities purchase steam from adjacent pulp and paper facilities. These facilities are typically chemical pulp mills that generate steam through efficient combined heat and power systems fueled primarily by biomass fuels. NCASI undertook an analysis of steam emission factor properties from operating kraft pulp mills within the US for the 2018 calendar year (NCASI 2021b) and summary results are provided in Table 14. Average GHG emission factors for steam purchases from US kraft mills range between 12.3 and 21.5 kg CO₂e/GJ steam, depending upon the allocation approach used to allocate the GHG burden to steam (NCASI 2021c). These emission factors are 20% to 34% of the emission profile for a 100% natural gas boiler with 80% thermal efficiency (emission factor of 62.6 kg CO₂e/GJ steam).

Table 14. Purchased Steam Emission Factors for Kraft Pulp and Paper Mills

Method	% of Emissions Allocated to Steam	GHG Emission Factor (kg CO ₂ e/GJ steam)	CO ₂ Emission Factor (kg CO ₂ /GJ steam)*	CH ₄ Emission Factor (kg CO ₂ e/GJ steam)**	N ₂ O Emission Factor (kg CO ₂ e/GJ steam)**
Method 1: Based on energy content	0.87	21.5	20.5	0.20	0.76
Method 2: Incremental based upon electricity	0.79	19.6	18.7	0.18	0.69
Method 3: Efficiency method	0.74	18.4	17.6	0.17	0.65
Method 4: Economic value method	0.50	12.3	11.8	0.11	0.43

* Biogenic CO₂ is not included.

** Global Warming Potentials (GWPs) from IPCC AR6 are used to convert CH₄ and N₂O emissions to CO₂e.

6.0 Carbon Capture and Storage or Use (CCS/U)

There are significant opportunities for the US pulp and paper sector in the area of carbon capture and storage or use. The sector has the potential to be a net negative GHG emitting industrial sector if economical approaches for bioenergy carbon capture and storage or utilization were to be implemented. Because industry recovery boilers are large single sources of biogenic emissions²⁴ they are particularly attractive candidates for bioenergy carbon capture and storage projects. Carbon capture and storage (CCS) is the capture of CO₂ emitted from stationary combustion point sources and storage in suitable long term storage reservoirs. Carbon capture and utilization (CCU) (oftentimes referred to as carbon capture and use), is the use of the captured CO₂ for the generation of a value-added end use. The end use of captured CO₂ can take the form of bulk chemicals, polymers, or fine chemicals; or the physical use of CO₂ for enhanced oil recovery (EOR), enhanced gas recovery (EGR), or enhanced coal bed methane (ECBM).

Carbon capture technologies that are at the pilot plant, demonstration, or commercial level are often described by technology route (Markewitz et al. 2012):

- Post-Combustion: CO₂ capture from the flue gas after the combustion step;
- Oxyfuel Combustion: Use of nearly pure oxygen (instead of air) for fuel combustion; or
- Pre-Combustion: CO₂ capture from reformed synthesis gas of an upstream gasification unit.

The carbon capture route can be described by the operating principle and includes absorption (e.g., via amines or ammonia), adsorption (e.g., via pressure or temperature swing), or other processes such as membrane separation, cryogenic distillation, or mineral looping.

6.1 Chemical Absorption Post-Combustion Techniques

When carbon dioxide is captured after the combustion step the process is described as “post-combustion” (Wang et al. 2011). Flue gas cleaning such as the removal of dust, sulfur, and nitrogen compounds is typically required as pretreatment prior to post-combustion carbon capture. The most promising post-combustion techniques are based on chemical absorption, where the carbon dioxide is segregated from the flue gas components with a solvent in an absorption tower and then desorbed/stripped from the solvent in a desorption/stripping tower. The most common solvents used are amines and ammonia.

Carbon capture with amines

The most mature chemical absorption post-combustion carbon technology is carbon capture with amines. Monoethanolamine (MEA) is the most commonly used amine solvent, and companies such as Mitsubishi Heavy Industries have developed proprietary sterically hindered (chemically modified with improved carbon capture properties) amines for carbon capture²⁵. Carbon capture technology with amines is available at commercial scale and has been installed at some fossil fuel power plants. The

²⁴ Biogenic CO₂ emissions from recovery boilers at large pulp and paper facilities can exceed one million metric tons of CO₂e annually.

²⁵ <https://solutions.mhi.com/ccus/co2-capture-technology-for-exhaust-gas-kmcd-r-process/>

largest installation to date is the Petra Nova²⁶ facility in Texas, which had the ability to capture 4776 metric tons of CO₂ per day but has since been mothballed because of operational issues and economic viability (IEEFA 2020).

The general approach to post-combustion carbon capture with amines is to treat wet, low CO₂ concentration flue gas and produce dry, high purity CO₂ for either compression and storage or utilization. The process train includes an absorption and stripping system. A block flow diagram of a hypothetical post-combustion CO₂ capture plant for kraft pulp and paper facilities is given in Figure 15. Flue gas is cooled to 40-60°C prior to being fed into the absorption tower. Low pressure steam is required for the stripper operation.

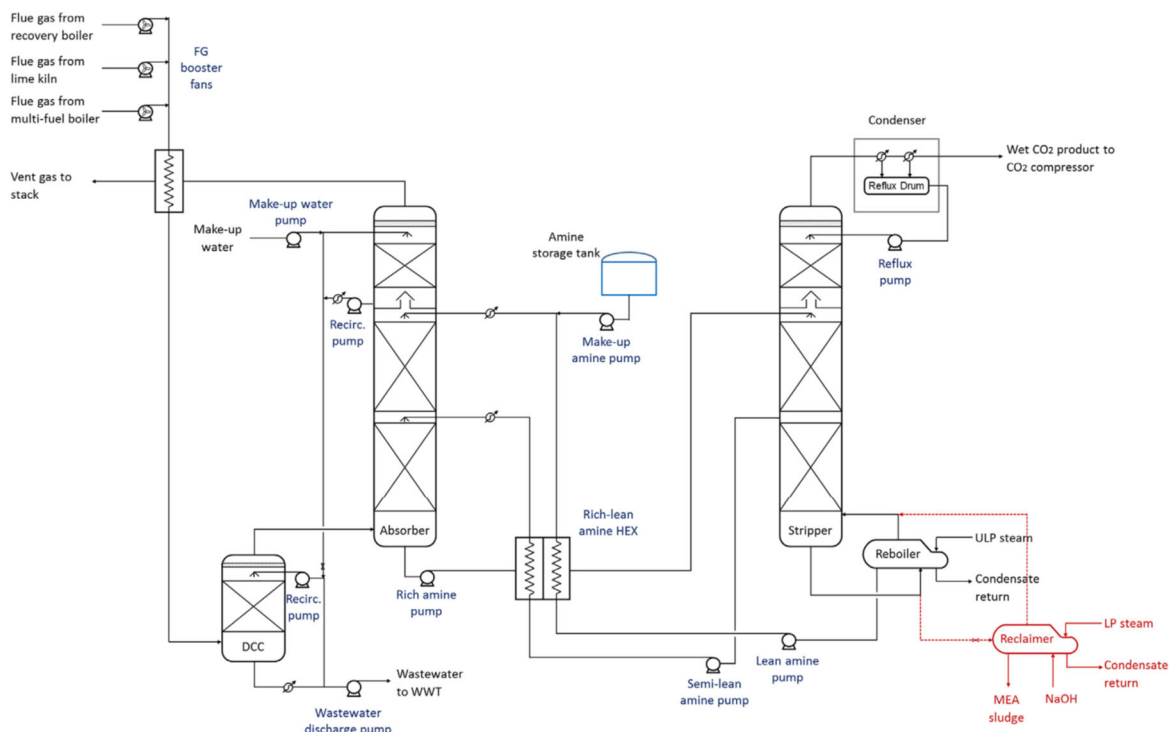


Figure 15. Block Flow Diagram of a Post-Combustion CO₂ Capture Plant (taken from Onarheim et al. 2017a)

The key parameters for design and operation of a post-combustion CO₂ capture unit are:

- Flue gas volume, which is critical for sizing of the absorption tower
- CO₂ content of the flue gas
- Purity of the captured CO₂

²⁶ Petra Nova is one of two carbon capture and sequestration power plants in the world. <https://www.eia.gov/todayinenergy/detail.php?id=33552>

Technical and economic challenges associated with operation of post-combustion carbon capture plants with amines include:

- Decomposition of the solvent in the presence of oxygen and dust
- Solvent degradation by reaction with flue gas sulfur dioxide and nitrogen oxide
- High energy requirements for the solvent regeneration step

Amines degrade in the presence of oxygen. Currently, inhibitors are required to prevent amine degradation from oxygen. Amines can react with SO_x and NO_x to form salts, which then must be removed via precipitation at high temperatures (Rao and Rubin 2002). SO₂ concentrations in the flue gas below 10 ppm are required to prevent amine salt formation. Table 15 shows typical impurity levels from combustion sources from the chemical pulp sector, as well as typical operational limits for post-combustion carbon capture with MEA.

Table 15. Typical Impurities in the Pulp and Paper Flue Gases (reported @ 6% O₂, dry) (IEAGHG 2016)

Impurities	Units	Typical Limit for MEA			
		Recovery Boiler	Multi-fuel Boiler	Lime Kiln	Application
SO _x	ppm	60	40	50	10-35
NO _x	ppm	11	14.1	16.9	20
Dust/PM	ppm	30 ^a	15	30 ^b	c

^a Fly ash could contain Na₂SO₄, Na₂CO₃.

^b Fly ash could contain CaO, CaCO₃.

^c Dust and particulate matter can cause amine degradation, solvent foaming, and plugging of process equipment, but there is no published recommendation of flue gas emission limits for PM for MEA absorption.

Figure 16 shows the specific regeneration energy within the absorber as a function of absorber packing height from one study, clearly showing the tradeoffs that exist between CAPEX and OPEX for carbon capture with MEA (Lawal et al. 2012). Figure 17 shows that the higher the CO₂ content in the flue gas the lower the specific energy required to regenerate the solvent. Recovery boiler flue gas CO₂ concentrations are around 13 mol %, power boilers ~12 mol %, and lime kiln CO₂ concentrations are around 20.5% mol % (Onarheim et al. 2017a). Accordingly, the specific regeneration energy required to capture CO₂ concentrations in typical pulp and paper flue gases should be lower than 4 GJ/mt of CO₂ captured.

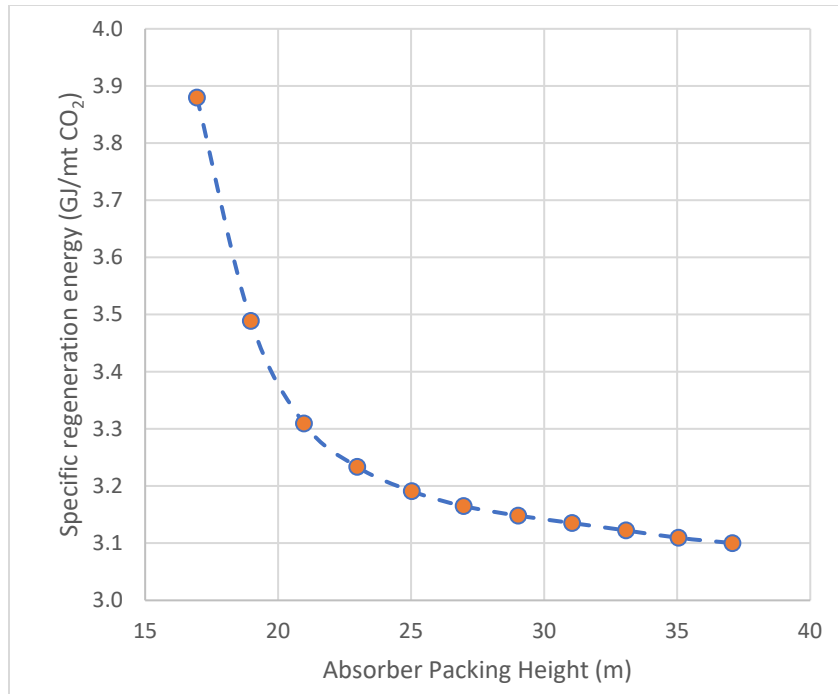


Figure 16. MEA Regeneration Energy as a Function of Absorber Packing Height (simulated data from Lawal et al. 2012)

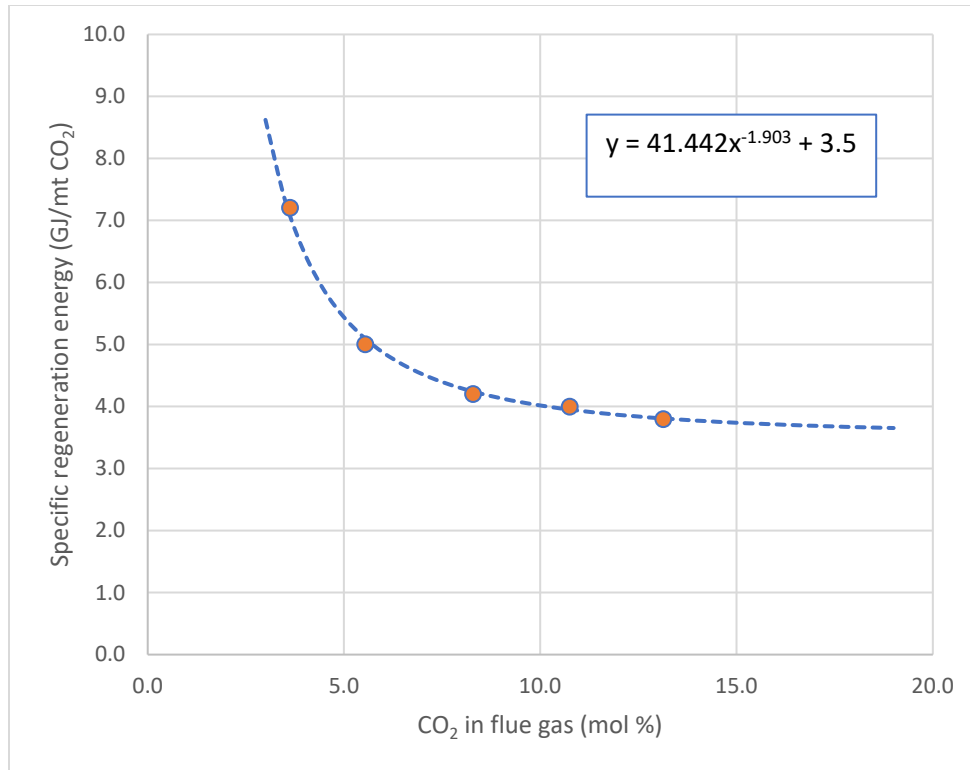


Figure 17. MEA Regeneration Energy
(data from Notz et al. 2012; data fit from Kouri 2016)

In a series of papers Onarheim et al. (2017a,b) examined the effect of retrofitting post-combustion CO₂ capture with MEA to a hypothetical Finnish market kraft mill and an integrated pulp and board mill. The authors evaluated the cost and performance of the mills with and without CCS. The process model of the two facilities included all relevant mill departments from wKood handling to pulp drying on the fiber side, and from evaporation to steam turbine on the chemical recovery and steam and power sides of the mill.

Heat is required for regeneration of the amine solvent. Ultra-low-pressure saturated steam at 2 bar was used in the work by Onarheim et al. (2017a,b), which was supplied from extraction and desuperheating low pressure steam for the turbine island. Figure 18 shows the low-pressure steam requirements as a fraction of mill CO₂ emission captured for the kraft market pulp mill. Steam requirements approach 8.5 GJ/adt as CO₂ capture percentages approach 100%. Figure 19 shows the electricity requirements as a fraction of mill CO₂ emissions captured. Electricity requirements approach 365 kWh/adt as CO₂ capture percentages approach 100%. The hypothetical market kraft mill had steam requirements of 9.6 GJ/adt, electricity consumption of 640 kWh/adt, and electricity export of 1,127 kWh/adt.

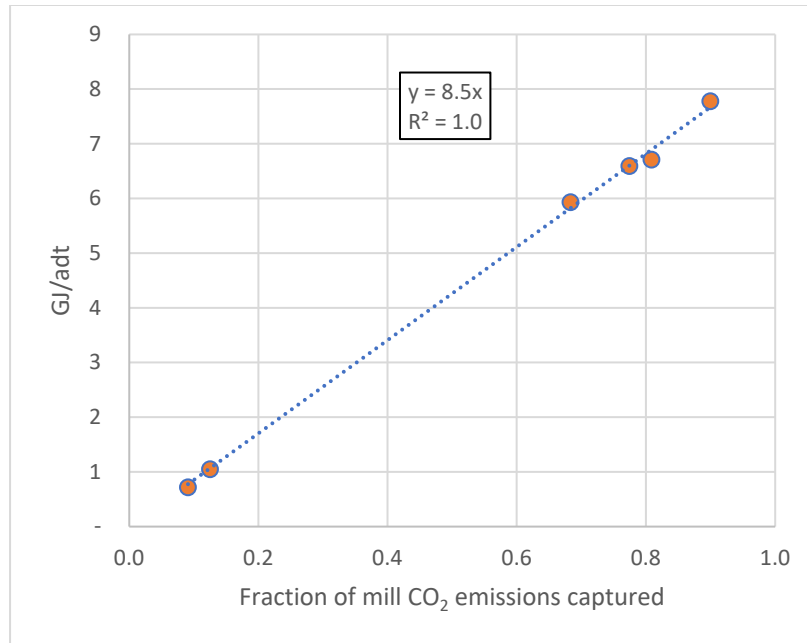


Figure 18. Low Pressure Steam Requirements as a Fraction of Mill CO₂ Emissions for a Kraft Market Pulp Mill (calculated values taken from Onarheim et al. 2017b)

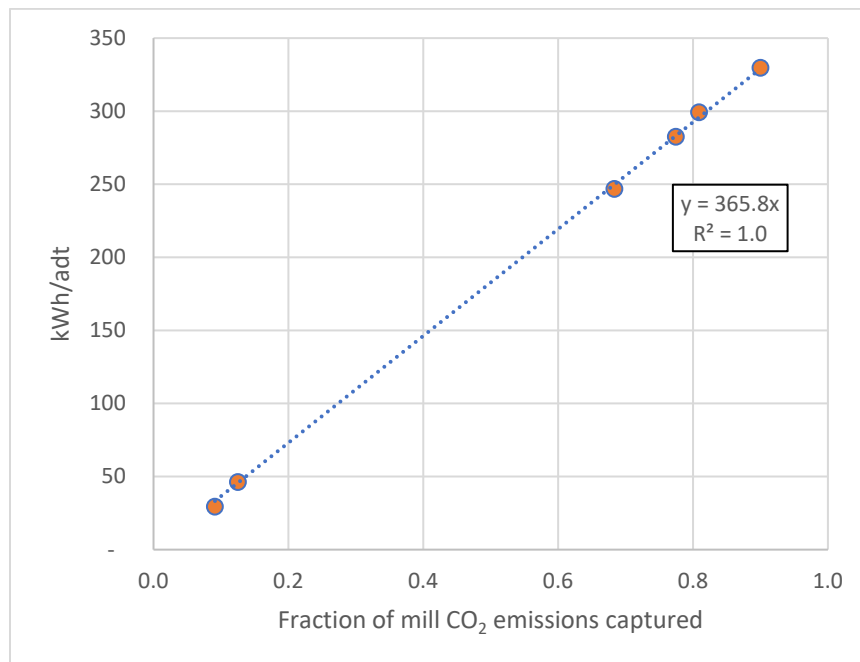


Figure 19. Electricity Requirements as a Fraction of Mill CO₂ Emissions for a Kraft Market Pulp Mill (calculated values taken from Onarheim et al. 2017b)

Figure 20 shows the low-pressure steam requirements as a fraction of mill CO₂ emission captured for the integrated market pulp and board mill. Steam requirements approach 14 GJ/adt as CO₂ capture percentages approach 100%. Figure 21 shows the electricity requirements as a fraction of mill CO₂ emission captured. Electricity requirements approach 110 kWh/adt as CO₂ capture percentages approach 100%. The hypothetical integrated pulp and board mills had steam requirements of 11.8 GJ/adt, electricity consumption of 990 kWh/adt, and electricity export of 666 kWh/adt.

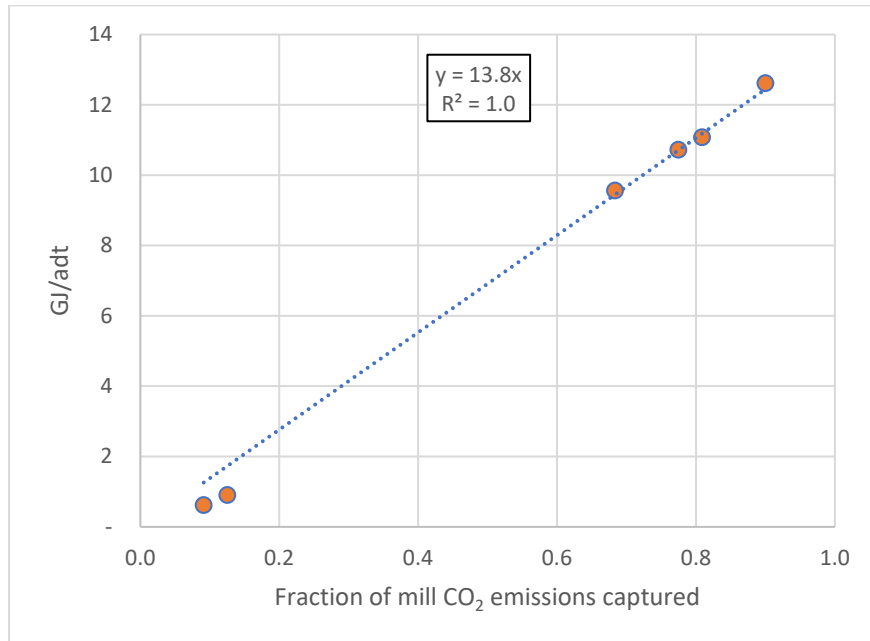


Figure 20. *Low Pressure Steam Requirements as a Fraction of Mill CO₂ Emissions for an Integrated Market Pulp and Board Mill (calculated values taken from Onarheim et al. 2017b)*

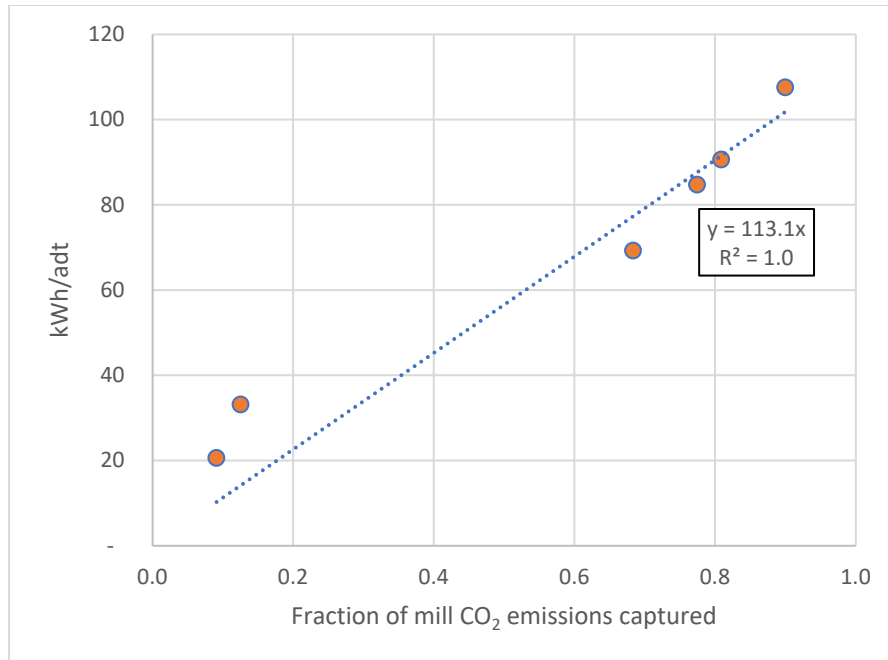


Figure 21. Electricity Requirements as a Fraction of Mill CO₂ Emissions for an Integrated Market Pulp and Board Mill (calculated values taken from Onarheim et al. 2017b)

Future advances for post-combustion carbon capture with amines include the development of more effective solvents such as sterically hindered (Bougie and Iliuta 2012) or tertiary amines (Chowdhury et al. 2013) to accelerate the absorption reaction and reduce desorption energy and energy needs for pumping and compression. The forest products sector needs to carry out pilot and demonstration projects for carbon capture technologies to ensure the compatibility of pulp and paper air emission sources with carbon capture technologies that use amines as solvents.

Chilled ammonia

The chilled ammonia process is a post-combustion carbon capture technique that takes advantage of the ammonia reactions with CO₂ to capture it from combustion flue gases. Ammonia reacts with CO₂ and water to form several ammonia carbonate precipitants. Ammonia may form ammonia carbonate, bicarbonate, carbamate, and sesqui-carbonate at temperatures in the range of 0-20°C, and preferably 0-10°C, hence the title “chilled ammonia” (Darde et al. 2010). Raising the temperatures reverses the reactions to liberate the CO₂. Combustion flue gas is cooled in a cooling system to lower the temperature of the flue gas to 0-10°C. The cooled flue gas then enters an absorption/desorption system. More than 90% of the CO₂ in the flue gas is typically removed in the absorption unit by reaction with ammonia solvent (typically up to 28 weight % ammonia). The ammonia is separated from the CO₂ in the desorption unit and regenerated for reuse. To achieve the separation of CO₂ and minimize ammonia emissions, the desorption unit operates at pressures in the range of 2-136 atmospheres and temperatures greater than 120°C. Because of the pressurized operation of the desorber, the energy requirements for compressing the final product CO₂ are reduced. The desorption reaction is endothermic but is lower than the endothermic reactions for amine desorption (Darde et al. 2010). A basic schematic of the chilled ammonia process for carbon capture is provided in Figure 22.

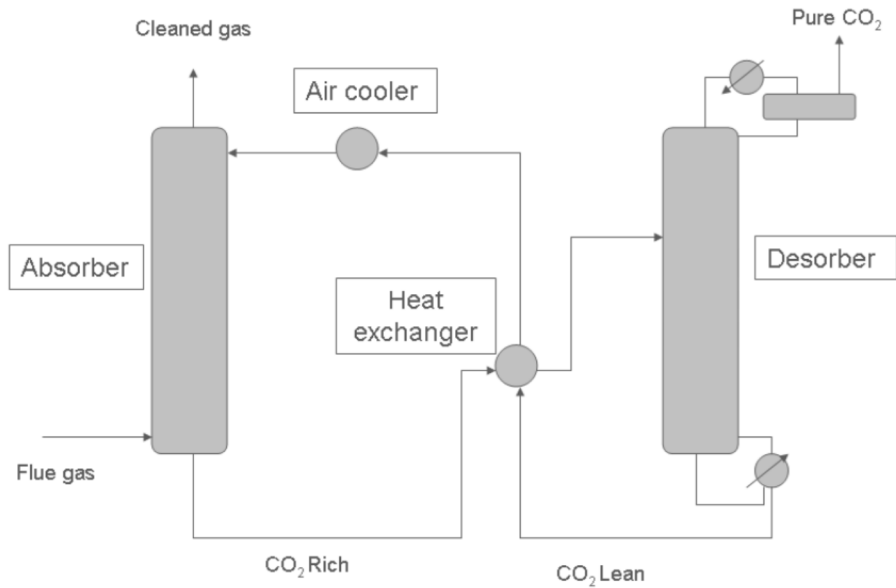


Figure 22. Process Flow Schematic for the Chilled Ammonia Process Modeling by Darde et al. (2010)

Darde et al. (2010) modeled the chilled ammonia process patented by Gal (2006)²⁷, examining the energy requirements and removal efficiencies. Process conditions for operation within the Gal patent are provided in Table 16.

Table 16. Process Conditions for the Chilled Ammonia System in the Patent by Gal (2006)

	Temperature (°C)	Pressure (atm)	CO ₂ Loading (mole fraction)
CO ₂ lean stream	0-20	1	0.25-0.67
Flue gas	0-10	1	
CO ₂ rich stream	50-200	2-136	0.5-1

Darde et al. (2010) determined energy requirements for the absorption/desorption process using the reference configuration for the absorber in Table 17 and reference configuration in the desorber in Table 18, and varying a number of operational parameters.

Table 17. Absorber Operating Configuration (Darde et al. 2010)

NH ₃ Initial wt%	T CO ₂ Lean Stream (°C)	T CO ₂ Rich Stream (°C)	T Flue Gas (°C)	Lean CO ₂ Loading	Rich CO ₂ Loading (mole fraction)
28	10	10	10	0.333	0.667

²⁷ <https://patentimages.storage.googleapis.com/97/41/c9/3e20a0f2764cc3/WO2006022885A1.pdf>

Table 18. Desorber Operating Configuration (Darde et al. 2010)

NH ₃ Initial wt%	T CO ₂ Lean Stream (°C)	T CO ₂ Rich Stream (°C)	T Pure CO ₂ (°C)	T H ₂ O + NH ₃ from the Condenser	Lean CO ₂ Loading	Rich CO ₂ Loading (mole fraction)
28	110	80	110	25	0.333	0.667

Darde et al. (2010) determined the energy requirements in the absorber at the conditions in Table 17 to be about -2,100 kJ/kg CO₂ absorbed, indicating the large cooling needs to maintain a low temperature target. The energy requirements in the desorber at the conditions in Table 18 were about 2,300 kJ/kg CO₂ captured. Figure 23 shows the impact of CO₂ loading on the energy requirements within the desorber and the importance of high CO₂ loading to minimize energy requirements. Figure 24 shows the impact of ammonia concentration on the energy requirements within the desorber. An initial mass fraction of ammonia of approximately 28% minimized the energy requirements within the desorber.

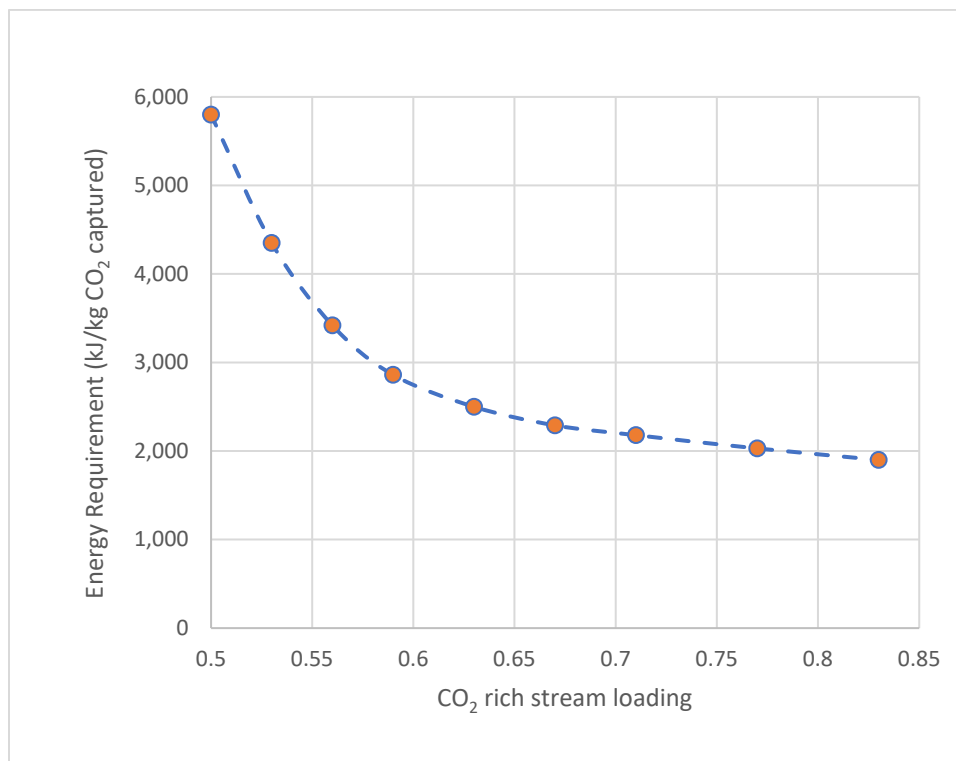


Figure 23. Energy Requirements as a Function of the Loading in the CO₂ Rich Stream (adapted from Darde et al. 2010)

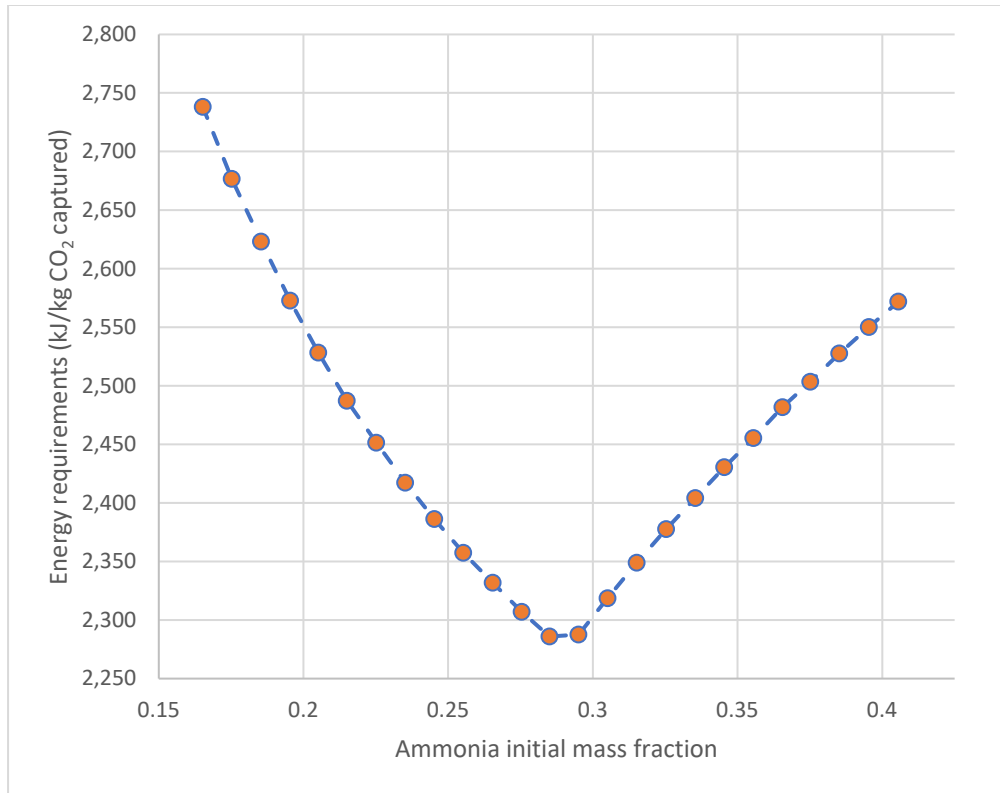


Figure 24. Energy Requirements as a Function of Initial Mass Fraction of Ammonia (adapted from Darde et al. 2010)

Kozak et al. (2009) provided information on an Alstom designed pilot-scale post-combustion chilled ammonia carbon capture plant designed to capture over 35 metric tons/day of CO₂. The key independent variables in operation were the flue gas flow rate, solution strength, and process temperature and pressure. The key performance metrics were CO₂ removal, ammonia slip²⁸ leaving with residual flue gas, heat and chilled water utility usage, and solvent usage. The goals of the pilot scale operation were to develop levelized costs for the system, determine process CO₂ removal costs, and determine the impact on electricity production at the power plant. A schematic of the Alstom chilled ammonia carbon capture system is provided in Figure 25. Pilot results showed higher ammonia slip than expected by design and CO₂ capture lower than the 90% design rate (due to operation of ammonia solution at half the design value). Additional information was provided by Alstom on their chilled ammonia carbon capture system in Power magazine²⁹. In addition to the 5-MW pilot plant detailed in Kozak et al. (2009), three other pilot scale facilities were outlined, including a 30-MW production validation unit for American Electric Power and a 40-MW production validation facility for Statoil in Norway. The performance penalty for adding a chilled ammonia CO₂ removal system to a supercritical pulverized coal fired power plant was 3.5% points out of the 40.5% HHV net efficiency associated with the power plant alone.

²⁸ Ammonia slip refers to the amount of ammonia passing through a reactor unreacted.

²⁹ <https://www.powermag.com/alstoms-chilled-ammonia-co2-capture-process-advances-toward-commercialization/>

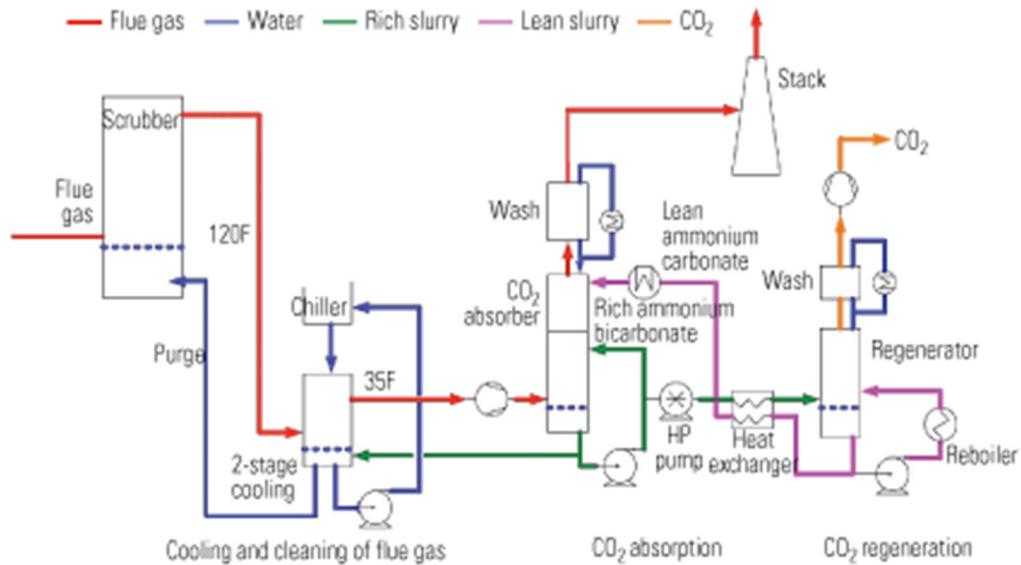


Figure 25. Schematic of a Chilled Ammonia Carbon Capture System from Alstom²⁹

6.2 Membrane Separation

Membranes are materials that selectively separate gases. Figure 26 demonstrates the principle of membrane operation. Commercial-level membranes have been used to separate CO₂ from natural gas. Current research is focused on developing dense, porous, or ion/electron conducting membranes for capturing CO₂ from power plant combustion sources (Markewitz et al. 2012).

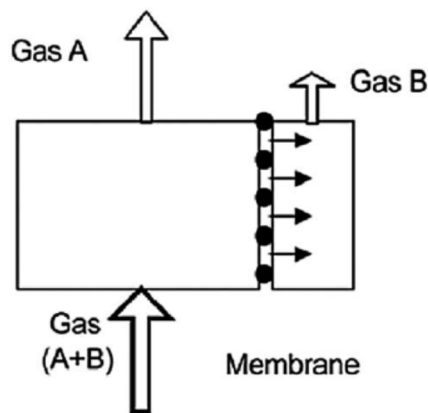


Figure 26. Gas Separation with Membranes (Markewitz et al. 2012)

Wang et al. (2017) reviewed the basic process designs for a membrane-based separations process for CO₂ capture. A typical schematic for a membrane separation process is provided in Figure 27. The authors evaluated the energy requirements and economic estimates of membrane systems for carbon capture compared to MEA-based chemical absorption and found no obvious advantage of membrane

systems over MEA systems in terms of both energy consumption and cost (Wang et al. 2017). Multi-stage or cascade membrane configurations are required to achieve CO₂ capture levels of 90% or greater (% of CO₂ removed from flue gas) and CO₂ purity of 95% or greater (% of CO₂ in the captured gas) (Wang et al. 2017; Zhai and Rubin 2013; Zhao et al. 2010). Polymeric membranes appear to be more flexible, durable, and efficient compared to other membrane materials at capturing CO₂ from industrial processes (Akpassi and Isa 2022) and are usually spiral wound or hollow fiber (Turi et al. 2017). A summary of energy requirements and economic performance of membrane systems for carbon capture is provided in Table 19, all from simulated operations. Studies referenced in Table 17 examined the technical viability and economic effects of post-combustion membrane carbon capture systems for coal-based power plants. All studies showed membrane post-combustion carbon capture technologies are characterized by significant efficiency penalties, either roughly equivalent or greater than those associated with amine-based capture systems.

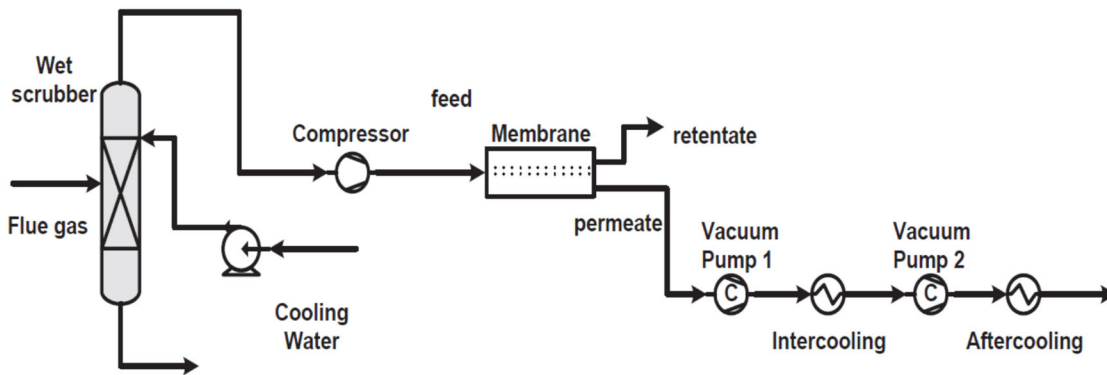


Figure 27. Schematic for a Membrane Separation Process (Wang et al. 2017)

Table 19. Energy and Economic Summary of Studies from Membrane-Based CO₂ Separation Processes

CO ₂ Capture (%)	Efficiency Loss (%)	Operating Temperature (°C)	Permeance (Nm ³ /m ² h bar)	Membrane Area (Mm ²), 1 st Stage/2 nd Stage	Power Plant Output (MW)	Reference
90	9.6	25	3	0.40/0.07	600	Maas et al. 2016
90	11.1	30	4.3	0.29/0.04	600	Maas et al. 2016
90	14.2	50	5	0.24/0.03	600	Maas et al. 2016
50	4.3	30	0.5	6.62/.24	600	Zhao et al. 2010
70	4.8	30	0.5	13.92/0.34	600	Zhao et al. 2010
70	6.4	30	3	2.44	600	Zhao et al. 2010
90	Not provided	30	Not provided	Not provided	450	Zhai and Rubin 2013

6.3 Chemical Looping

In a carbonate looping process, a mineral oxide (MO) is carbonized with CO₂ to form a mineral carbonate (MCO₃). The mineral carbonate is calcined in a subsequent reactor to regenerate the mineral oxide and liberate the carbon dioxide. A schematic of the carbonate looping process is provided in Figure 28. Calcium looping (CaL) is the most attractive mineral looping process due to the inexpensive and high availability of the calcium-based starting materials, but in principle other mineral compounds can be used (Gadikota 2021). Calcium looping was first proposed by Shimizu et al. (1999) and is particularly attractive to the cement (Arias et al. 2017) and pulp and paper industries (Santos et al. 2021) due to their first-hand knowledge of the calcination process in lime kilns.

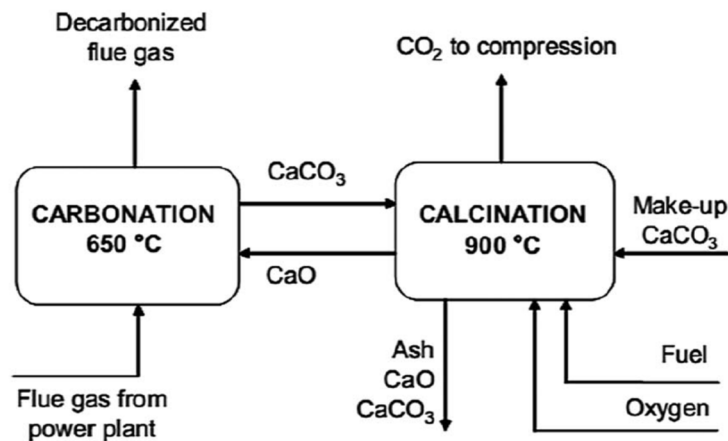


Figure 28. Schematic of a Carbonate Looping Process (Markewitz et al. 2012)

The carbonation and calcination reactions, along with the heat of reaction, are given below (Grace et al. 1989).



Santos et al. (2021) investigated integration of the CaL process into the kraft process. The CaL process, CO₂ compression unit, and steam cycle were modeled by replacing an existing lime kiln from a model kraft mill with a kiln of larger capacity, interconnected with a carbonator (see Figure 29). Fresh limestone feed is required to maintain average conversion in the carbonator. In the kraft pulp mill example, the make-up feed is a combination of lime mud from the causticizing plant and fresh limestone. A portion of the resulting CaO is returned to causticizing, and the remainder is sent to the carbonator.

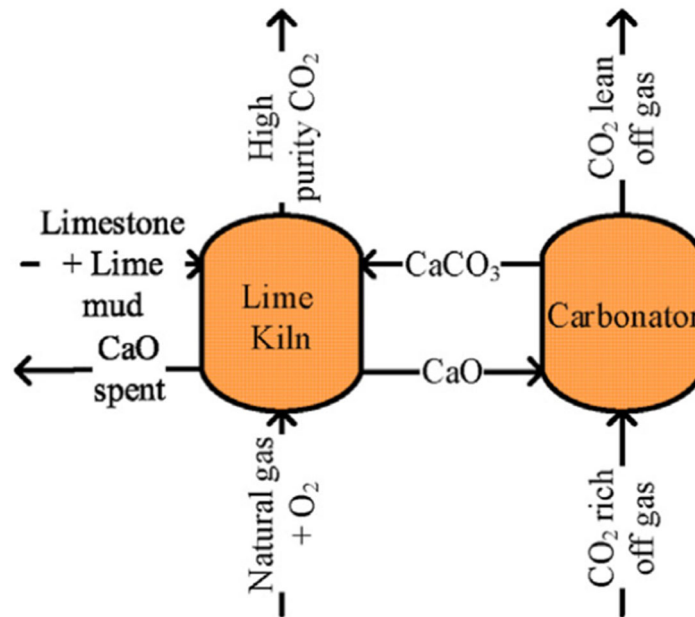


Figure 29. Schematic of a Calcium Looping Process (Santos et al. 2021)

Calcium looping for carbon capture has been tested at the pilot scale (1.7 MW_{thermal}) based on two circulating fluidized bed reactors treating up to 2,400 kg/hr of CO₂ in the carbonator (Sánchez-Biezma et al. 2013), and more recently up to 20 MW_{thermal} at the pilot scale (Hilz et al. 2019). Carbon dioxide capture efficiencies of over 90% were observed during the pilot process. In principle, the CaL process can be added as a stand-alone post-combustion system not affecting the operation or the kraft recovery system, but with significant potential energy savings through heat integration (Santos et al. 2021; De Lena et al. 2017).

6.4 Cryogenic Carbon Capture

Cryogenic carbon capture operates on the principle of phase change to separate CO₂ from gas mixtures, i.e., the phase change of CO₂ from a gaseous to a liquid or solid form allows for its physical separation from the gas stream. Advantages of cryogenic CO₂ capture are that no chemical absorbent is required, and liquid or solid carbon dioxide is produced, which facilitates transport and storage.

Font-Palma et al. (2021) reviewed cryogenic carbon capture techniques, their feasibility of high CO₂ recovery rates and purity levels, benefits compared to other carbon capture technologies, and barriers to commercialization. Cryogenic distillation is the most well-established cryogenic separation technology and achieves separation based on the difference in boiling points of CO₂ and other air constituents such as nitrogen, oxygen, and argon. Cryogenic distillation is currently used for the industrial production of oxygen, nitrogen, and argon (and other rare gases), and the removal of impurities (e.g., H₂S and CO₂) from natural gas. Typically, CO₂ and water vapor are removed from air prior to fractional air distillation because the operating temperatures in the distillation tower (-80°C to -200°C) lead to water and CO₂ solid formation that causes equipment plugging. Figure 30 shows a schematic of a cryogenic distillation system.

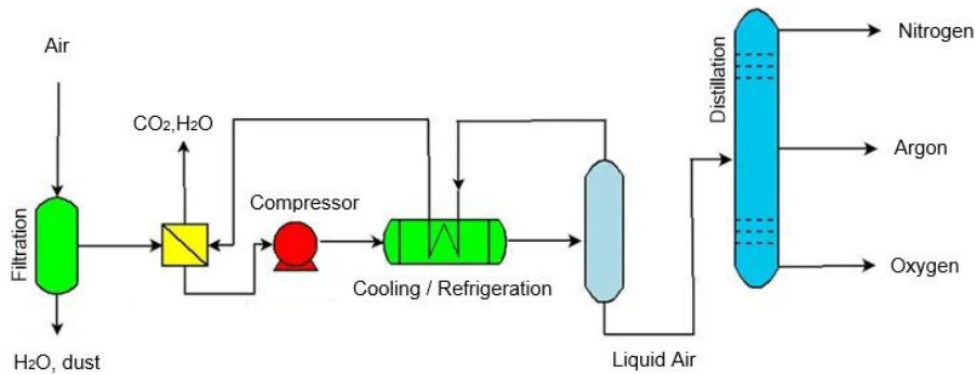


Figure 30. Schematic of a Cryogenic Distillation System³⁰

Stirling coolers are refrigerators designed to reach cryogenic temperatures of below -153°C and utilize the Stirling thermodynamic cycle. Song et al. (2017) designed and evaluated a process comprised of three Stirling coolers that (1) precool the feed gas to condense water vapor, (2) freeze CO_2 , and (3) store the CO_2 at cryogenic temperatures. The system attains 95% CO_2 recovery and uses $2.62 \text{ MJ}_{\text{electric}}/\text{kg CO}_2$ captured, which can be reduced to $1.37 \text{ MJ}_{\text{electric}}/\text{kg CO}_2$ with heat integration. A schematic of the process is given in Figure 31.

Packed and moving packed beds have been proposed for cryogenic CO_2 capture. During the cooling step, cryogenically cooled nitrogen gas is fed into a packed bed to precool the bed material. Once the bed is cooled, the gas containing CO_2 is fed into the packed bed. The CO_2 deposits as a solid onto the surface of the bed material until saturation is obtained throughout the column. Turnier et al. (2011) simulated a system of three packed beds operating in parallel and cycling between capture, regeneration, and cooling in a semi-continuous process. Cooling duty ranged between $1.2\text{-}2.6 \text{ MJ}_{\text{electric}}/\text{kg CO}_2$ and was dependent upon initial bed temperature and concentration of CO_2 in the flue gas (Turnier et al. 2011). With moving packed beds the cooling packing material is removed from the packing column using a screw conveyor and transported to a sublimation unit. Moving packed beds have the advantage over fixed beds by preventing excessive accumulation of solid CO_2 within the capture column. Willson et al. (2019) estimated the specific energy requirements of a moving bed CO_2 capture system at $0.95 \text{ MJ}/\text{kg CO}_2$ (2019).

³⁰ <https://www.theengineersperspectives.com/cryogenic-distillation-process/>

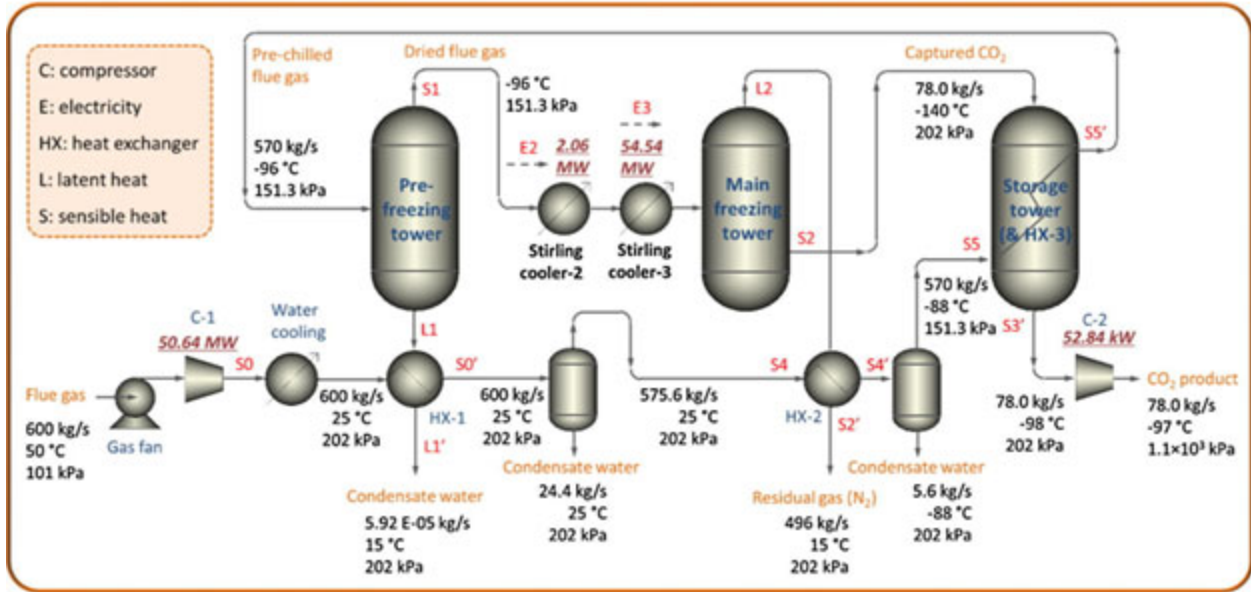


Figure 31. Cryogenic CO₂ Capture Process Using Stirling Coolers (Song et al. 2017)

With the cryogenic liquids approach, the gas containing CO₂ is directly contacted with a cryogenic liquid causing formation of a solid CO₂ slurry, which is subsequently treated via filtration to produce a pure CO₂ product. Through bench-scale and modeling work, the energy penalty was calculated at 0.74 MJ_{electric}/kg CO₂ at a 90% CO₂ capture rate (Jensen et al. 2015). Table 20 shows the energy requirements of various carbon capture technologies, with cryogenic methods highlighted, from the review of Font-Palma et al. (2021). Cryogenic cooling technologies are currently available at commercial scale but have not been applied to CO₂ separation in industrial flue gases at the commercial scale level.

Table 20. Energy Needs for Various Carbon Capture Methods
Cryogenic methods are in bold. (Summarized by Font-Palma et al. 2021)

Carbon Capture Method	Energy Duty (MJ/kg CO ₂)
Cryogenic liquids	0.74
Stirling coolers	1.37
Cryogenic distillation	1.47
Cryogenic packed bed	1.2-2.6
Cryogenic moving bed	0.95
Absorption	0.87-4.2
Adsorption	0.36-4.2
Membranes	0.24-1
Oxy-fuel combustion	1.15-2.0

6.5 Direct Air Capture

The principle of direct air carbon capture (DAC) is to remove CO₂ directly from the atmosphere through large fans that draw ambient air into the DAC unit. DAC is not focused on capturing CO₂ from stationary, fixed, concentrated sources like combustion units, and thus its target may be fugitive sources. Membranes capture carbon dioxide, which can be released upon heating of the filter material. The concentrated CO₂ can either be used or stored. Disadvantages of DAC systems are the large energy requirements to capture low concentrations of CO₂ in the atmosphere (~0.04% CO₂ in the atmosphere compared to 10-18% in flue gases from combustion sources or lime kilns) and the low capture rates. McQueen et al. (2020) provided a cost analysis of DAC and sequestration and estimated total cost of capture (capital and operating) of \$223, \$205, and \$233/metric ton of CO₂ captured for the base case, geothermal, and nuclear case studied.

The Orca facility operating in Iceland (Figure 32) is one of the largest DAC systems currently operational and removes 4,000 metric tons of CO₂ from the atmosphere per year. Advantages of DAC systems are that they can be sited in locations with abundant renewable energy to power operations and sited in locations with geology amenable to long-term carbon storage.



Figure 32. Orca Direct Air Capture Facility in Hellisheiði, Iceland³¹

³¹ <https://www.sciencefocus.com/future-technology/carbon-capture-in-action/>

Occidental and 1PointFive announced plans for detailed engineering and early site construction of a DAC plant in Ector County, Texas³². Start-up of the plant is expected in late 2024. Upon completion, the plant will be the largest DAC plant in the world, with the capacity to capture up to 500,000 metric tons of CO₂ per year and with the capability to scale up to 1 million metric tons per year.

6.6 Pre-Combustion Techniques

With pre-combustion techniques the fuel is pre-treated to capture CO₂ before the fuel is burned, thus preventing the release of CO₂ to the atmosphere. The pre-treatment consists of converting the fuel to syngas (a mixture of hydrogen and CO) through gasification, and then subjecting the syngas to a water-gas shift reactor. In the water-gas shift reactor the syngas reacts with steam to convert CO to CO₂ and additional hydrogen. The syngas exiting the water-gas shift reactor has a CO₂ concentration of ~40% and can be more economically treated using a variety of CO₂ removal methods. Once the CO₂ is removed, the remaining gas, primarily consisting of hydrogen, is combusted in a gas turbine for electricity generation. An air separation unit, prior to the gasification unit, removes nitrogen to increase gasification yield and reduce the size of the system components. Figure 33 shows a schematic of a post-combustion CO₂ removal system, and Figure 34 shows a schematic of a pre-combustion CO₂ removal system.

The pulp and paper sector has a long history developing gasification technologies applied to biomass (Knight et al. 2009) and black liquor (Whitty and Verrill 2004); however, cost and operational issues have limited adoption of these technologies by the sector.

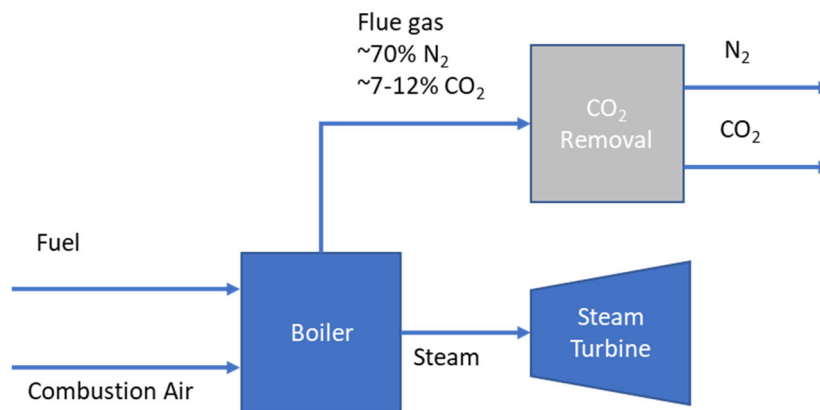


Figure 33. Post-Combustion CO₂ Removal

³² <https://www.oxy.com/news/news-releases/occidental-1pointfive-to-begin-construction-of-worlds-largest-direct-air-capture-plant-in-the-texas-permian-basin/>

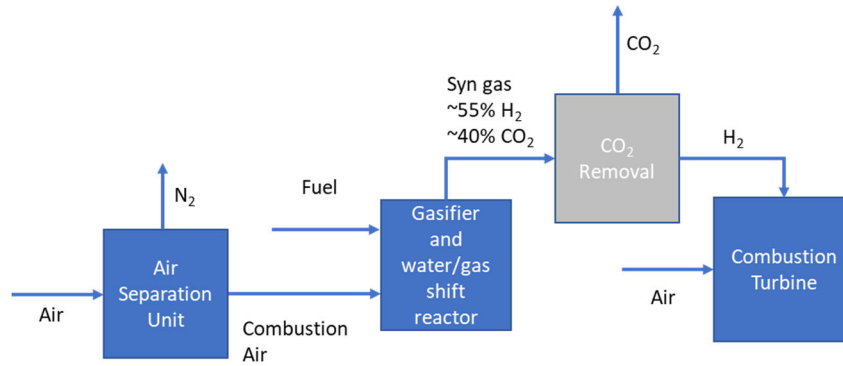


Figure 34. Pre-Combustion CO₂ Removal

6.7 Oxy-Combustion

In an oxy-combustion process, fuel is combusted in an oxygen-rich environment, resulting in flue gas with higher CO₂ content than that in flue gas from combusting the same fuel in air. An air separation unit is necessary to remove almost all nitrogen from the air so that a gas stream primarily consisting of oxygen (95%) is used for combustion. A basic schematic of the oxy-combustion process is provided in Figure 35. The oxy-combustion process produces a combustion flue gas that is approximately $\frac{2}{3}$ CO₂ on a volume basis, which can be directed to a subsequent purification and compression system to generate high-purity CO₂ (see Figure 36).

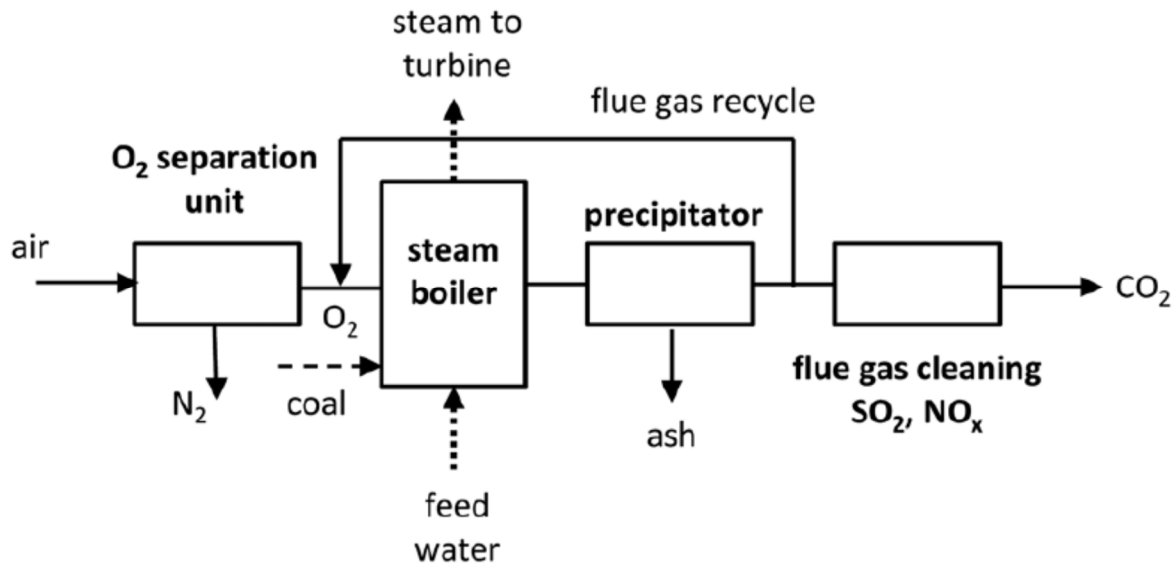


Figure 35. Schematic of an Oxyfuel Combustion Process (Markewitz et al. 2012)

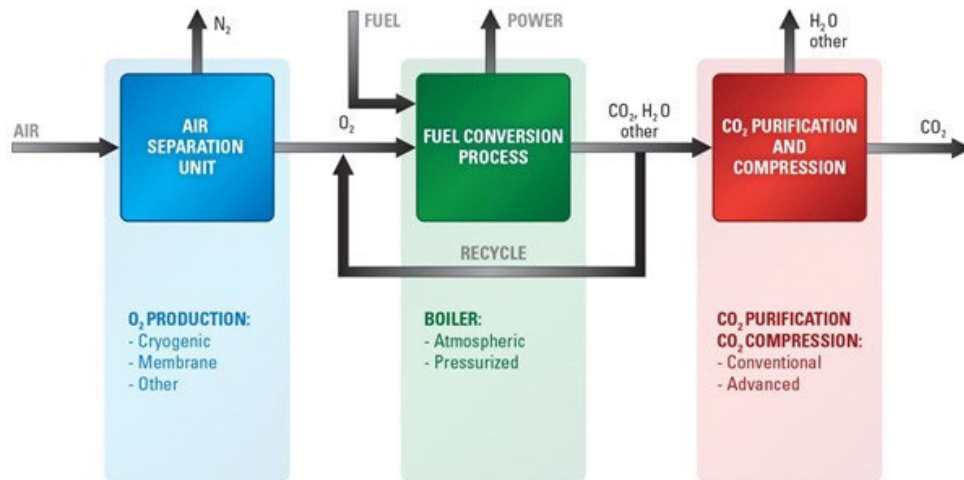


Figure 36. Oxyfuel Combustion Process with Add-On Carbon Capture³³

Oxygen for the combustion process is currently produced by cryogenic air separation, in which oxygen is removed from air by condensation at temperatures below -182°C. There are several techniques for industrial oxygen production depending on oxygen flowrate and purity requirements (see Figure 37).

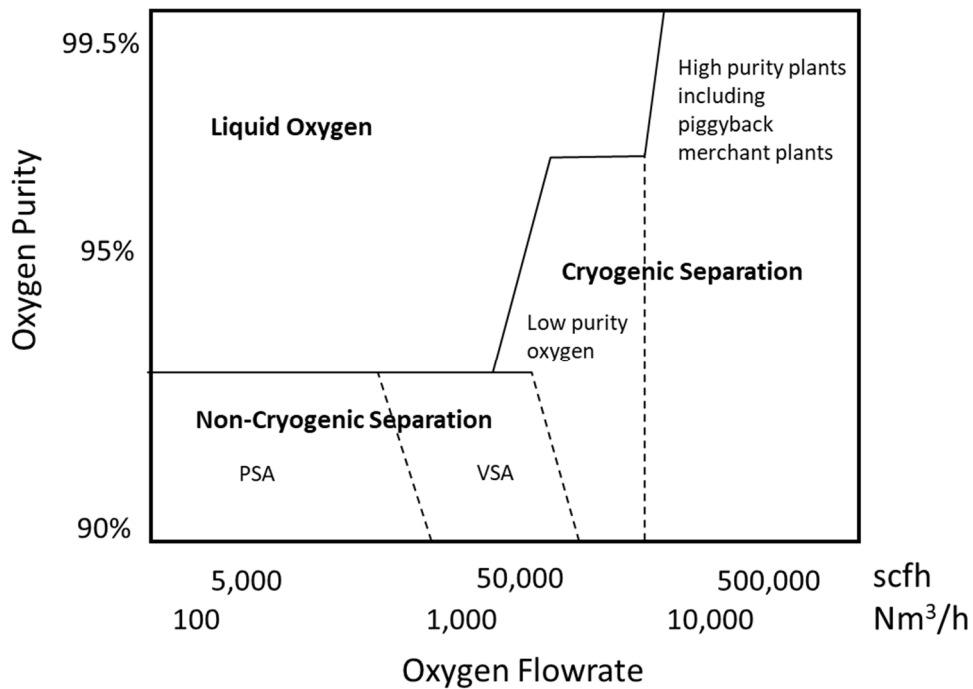


Figure 37. Approximate Lowest Cost of Oxygen Supply Methods for New Plants (Adapted from Universal Industrial Gases³⁴)

³³ <https://www.netl.doe.gov/node/7477>

³⁴ <https://www.uigi.com/optimalplant.html>

All industrial oxygen production techniques are energy-intensive and use electricity as the driving force to separate oxygen from air. A summary of energy requirements for oxygen production is provided in Table 21.

Table 21. Energy Requirements for Oxygen Production (Bisio et al. 2002)

Method	Oxygen Purity	kWh/metric ton O ₂
Cryogenic separation	50%	400
Cryogenic separation	>99%	1,100
Pressure swing adsorption (PSA)	90%	550
Perm-selective membrane	37.5	210
Perm-selective membrane	44	300

Oxyfuel combustion has altered combustion radiative heat transfer properties due to the differing proportions of H₂O and CO₂ from the combustion process compared to air combustion, and the higher combustion temperatures in the combustion chamber. For this reason, oxyfuel boilers require redesigned heat transfer surfaces, combustion chamber geometries, and optimized flue gas routing systems compared to air-based combustion systems (Markewitz et al. 2012), thereby making retrofit of existing combustion systems a challenging task. Pilot-scale oxy-combustion systems for coal have been developed by Alstom (15 MW_{thermal})³⁵ and Babcock & Wilcox (30 MW_{thermal})³⁶. B&W provided oxy-fuel technology for use with the retrofit of a 167 MWe coal-fired power plant; however, the project was canceled in 2016 due to redirection of DOE funding support.

6.8 Comparison of Carbon Capture Techniques

Post-combustion carbon capture with MEA and ammonia are the most mature chemical absorption carbon capture technologies. Basic properties of MEA and NH₃ are provided in Table 22. The MEA solvent is more expensive than ammonia. The chilled ammonia system must operate at low temperatures (0-10°C) for best performance and higher regeneration pressures (20-40 bar compared to 1-1.5 bar for MEA systems).

Table 22. Basic Properties of MEA and NH₃ (taken from Black 2006³⁷)

Property	MEA	NH ₃
Molecular weight	61	17
Practical CO ₂ loading (kg/kg solution)	0.05	0.1 – 0.2
Heat of reaction (Kcal/g mol)	20-22	6-8
Absorption temperature (°C)	40-70	0-10
Regeneration temperature (°C)	110-130	110-130
Regeneration pressure (bar)	1-1.5	20-40
H ₂ O/CO ₂ in regenerator gas outlet (mole ratio)	1-1.5	0.01-0.05
Makeup requirements (kg/ton CO ₂)	2	0.2
Makeup cost (US\$/ton)	1,000-1,500	200-300

³⁵ <https://www.osti.gov/servlets/purl/1126719>

³⁶ <https://www.babcock.com/home/environmental/decarbonization/oxy-fuel-combustion/>

³⁷ Black, S. 2006. Chilled Ammonia Scrubber for CO₂ Capture. Alstom presentation hosted on MIT's CC&ST Program website. https://sequestration.mit.edu/pdf/forum7/6B_Black.pdf

Kothandaraman (2010) modeled several solvent systems for carbon capture to determine mass transfer characteristics, overall energy consumption in the CO₂ capture and compression system, and sizing of equipment. An MEA system for a natural gas combined cycle and coal power plant was evaluated as a base case system. In the MEA system, the energy penalty from CO₂ regeneration accounted for 60% and 53% of the energy penalty for the coal and natural gas system, respectively, and the compression work accounted for 29% and 19% for the coal and natural gas system, respectively. The remainder of the energy requirements were associated with blower energy and auxiliaries. Process flexibility was limited by MEA degradation reactions, and different flowsheet configurations did not improve energy efficiency significantly (Kothandaraman 2010). The chilled ammonia system led to a 32% reduction in power plant output relative to a plant equipped with the MEA system. Refrigeration in the absorber accounted for 44% of the energy requirements, and CO₂ regeneration accounted for 35% of the energy requirements. Compression and auxiliaries accounted for the remaining energy. The work by Kothandaraman shows that depending upon the solvent, the energy breakdown for component operations is different.

Table 23 provides a comparison of the advantages and disadvantages of classes of carbon capture technologies, as well as achievable operating limits. Many of the raw materials used in carbon capture have their own substantial energy footprint. For instance, MEA is produced by treating ethylene oxide with aqueous ammonia; ammonia is produced in the Haber-Bosch process, which converts hydrogen and nitrogen to ammonia at high temperature and pressure; and cryogenic air separation is used to produce pure oxygen for oxy-combustion.

Table 23. Comparison of Classes of Carbon Capture Technologies
(from Leung et al. 2014; Akpasi and Isa 2022; Font-Palma et al. 2021)

Separation Method	Post-Combustion Capture	Pre-Combustion Capture	Oxy-Combustion
Advantages	<ul style="list-style-type: none"> • Retrofit of existing industrial plants 	<ul style="list-style-type: none"> • Treatment of a syngas with higher CO₂ concentrations than other technologies 	<ul style="list-style-type: none"> • High carbon capture efficiency • Absence of NO_x in flue gas
Disadvantages	<ul style="list-style-type: none"> • Solvent subject to oxidative degradation • Ammonia air emissions from MEA degradation 	<ul style="list-style-type: none"> • Syngas pretreatment and drying is required prior to CO₂ capture • No retrofitting opportunities 	<ul style="list-style-type: none"> • Difficult to retrofit exiting industrial plants
Pretreatment of combustion flue gas	<ul style="list-style-type: none"> • SO_x and NO_x removal necessary to limit solvent degradation • Flue gas must be cooled 	<ul style="list-style-type: none"> • Syngas pretreatment and drying required • SO_x removal is required 	<ul style="list-style-type: none"> • Flue gas recycling is needed for temperature control
Limits of CO ₂ concentration in flue gas (vol %)	4-14	15-40	78-80
CO ₂ capture efficiency (%)	85-90	85-90	90-100
Achievable CO ₂ purity (%)	99.6-99.8	85-99	87.0-94.8
Technology status	Commercial (TRL 9)	Demonstration (TRL 7)	Demonstration (TRL 7)
Combustion medium	Air	Air and steam	High purity O ₂

The International Energy Agency (IEA) Greenhouse Gas Research & Development Programme commissioned a study of additional costs associated with carbon capture technologies (IEA 2006). This study was undertaken in 2006 by the consultant Mott MacDonald and is based upon Mott MacDonald’s long-run forecast of fuel prices (US\$2.2/GJ LHV for bituminous coal and US\$7.8/GJ LHV for natural gas) to 2025. The summary in Table 24 is based upon responses from public and private power utilities, project developers, equipment suppliers, and project lenders. Post-combustion carbon capture technologies had the lowest impact on plant efficiency, lowest capital costs, and among the lowest electricity costs. Dillon et al. (2013) presented technological and economic results of retrofitting several operating coal-fired power plants (versus theoretical plants found in the literature) with post-combustion carbon capture technology. Table 25 shows the net efficiency loss associated with the installation of carbon capture technology. The thermal efficiency penalty for retrofitting existing power plants is significantly greater than what is outlined in Table 24. The authors also presented information on a new-build ultra-supercritical (USC) pulverized coal (PC) plant. The efficiency penalty for a USC PC plant was 12.2 percentage points, 32% greater than the efficiency penalty in Table 24.

Table 24. *Efficiency Losses and Costs Associated with Classes of Carbon Capture Technologies (IEA 2006)*

Technology	Thermal Efficiency (% LHV)	Capital Cost (\$/kW)	Electricity Cost (cents/kWh)	Cost of CO ₂ Avoided (\$/ton CO ₂)
Natural gas-fired plants				
No capture	55.6	500	6.2	-
Post-combustion capture	47.4	870	8.0	58
Pre-combustion capture	41.5	1180	9.7	112
Oxy-combustion	44.7	1530	10.0	102
Coal-fired plants				
No capture	44.0	1410	5.4	-
Post-combustion capture	34.8	1980	7.5	34
Pre-combustion capture	31.5	1820	6.9	27
Oxy-combustion	35.4	2210	7.8	36

Table 25. *Effect on Power Plant Efficiency by Installation of Post-Combustion Carbon Capture*

US Site	Fuel	Calculated Net Efficiency Penalty (%)
Bayshore	Petcoke	14.0
Lingan	Bituminous coal	12.0
Powerton	Sub-bituminous coal	11.6
Coal Creek	Lignite	12.0
Intermountain	Blend of bituminous and sub-bituminous coal	11.0
New build USC plant	Powder River Basin (PRB) sub-bituminous coal	12.2

Table 26 provides a comparison of the advantages and disadvantages and achievable operating limits of post-combustion carbon capture technologies reviewed in this white paper, compiled from several authors.

Table 26. Comparison of Post-Combustion Carbon Capture Technologies
 (Font-Palma et al. 2021; Akpasi and Isa 2022; Mondal et al. 2012; Arias et al. 2017; De Lena et al. 2017)

Technology	Chemical Adsorption	Absorption	Membrane	Cryogenic	Calcium Looping
Advantages	<ul style="list-style-type: none"> • Sorbents can be regenerated by heating and/or depressurization • Most mature process for CO₂ separation 	<ul style="list-style-type: none"> • Process is reversible and the absorbent can be recycled • Low cost of sorbents 	<ul style="list-style-type: none"> • Process has been adopted for separation of other gases 	<ul style="list-style-type: none"> • Mature technology • Adopted for many years in the industrial gas sector for CO₂ recovery 	<ul style="list-style-type: none"> • Low cost and wide availability for limestone • Regeneration of sorbent • High temperature process entailing opportunity for heat integration • Integrated add-on system opportunities
Disadvantages	<ul style="list-style-type: none"> • Absorption efficiency depends upon CO₂ concentration • Environmental impacts related to sorbent degradation 	<ul style="list-style-type: none"> • Requires adsorbent capable of operating at elevated temperatures 	<ul style="list-style-type: none"> • Operational issues include low fluxes and membrane fouling • No regeneration process • Not suitable for high temperature operation so requires cooling of combustion flue gases 	<ul style="list-style-type: none"> • Only viable when CO₂ product concentration is >90% v/v • Necessary to remove water, NO_x, SO_x, and other trace components to avoid freezing and plugging of equipment 	<ul style="list-style-type: none"> • Limits to carbonation conversion (thermodynamic capture efficiency of 96%) • Constant purge and make-up for operation • Removal of SO_x needed to prevent excess CaSO₄ formation
Inlet CO ₂ concentration (vol. %)	<30.4	28-34	11.8	<90	10-27.4%
CO ₂ capture efficiency (%)	95	<85	90	99.9	90
CO ₂ purity (%)	99	99.98	95	99.95	-

Scale	Commercial (270 MW _e)	-	-	-	Pilot (MW _{thermal}) scale
Energy requirement (MJ/kg CO ₂)	4-6	2-9.2	0.5-6	2.4-10	2.8-3.9
Operating flexibility	Moderate	Moderate	High (CO ₂ > 20%) Low (CO ₂ <20%)	Low	-
Response to variations	Rapid (5-15 min)	-	Instantaneous	Slow	-
Start-up time after a plant shutdown	1 hr	-	10 min	8-24 hr	-
Turndown (ability to operate at levels lower than design)	Down to 30%	-	Down to 10%	Down to 50%	-
Reliability	Moderate	Moderate	100%	Limited	-
Process control Requirement	High	High	Low	High	-
Ease of expansion	Moderate	Moderate	Very high	Very low	Moderate

Technology Readiness Level for Carbon Capture

The Technology Readiness Level (TRL) is a ranking system for technologies to gauge the state of commercial development. The Electric Power Research Institute (EPRI) adapted the basic TRL framework originally developed by NASA to assess the maturity of carbon capture technologies (Freeman and Brown 2011). Table 27 shows the EPRI adaptation of the TRL framework for carbon capture technologies.

Table 27. EPRI TRL Definitions for Use with CO₂ Capture Processes
(taken from Freeman and Brown 2011)

Technology Readiness Level (TRL)		
Technology State	Level	Description
Demonstration	9	Normal commercial service
	8	Commercial demonstration, full scale deployment in final form
	7	Sub-scale demonstration, fully function prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles observed, initial concept

EPRI has continued their global monitoring of the carbon capture technology landscape at least through 2016³⁸. Figure 38 shows a TRL distribution of post-combustion CO₂ capture processes ranked by EPRI in the 2011 timeframe. Figure 39 shows the TRL distribution of post-combustion CO₂ capture processes using the same EPRI ranking process in the 2016 timeframe. Between 2011 and 2016 some absorption processes have moved towards commercialization with technologies at TRL levels of 8 and 9 and presumably some technologies are no longer viable because of the differences in evaluated processes in Figure 38 and Figure 39.

Two technologies that have developed rapidly between 2011 and 2016 are calcium looping and the chilled ammonia process. Calcium looping has advanced rapidly over the past decade to reach TRL 6-7, and it has been tested in several pilot plants up to the MW_{thermal} scale (Arias et al. 2017). The chilled ammonia process (CAP) was successfully demonstrated at TRL 7 at the Mongstad Technology Center using flue gas streams with high (16% CO₂) and low (3.6% CO₂) CO₂ concentrations³⁹.

Table 28 shows the TRL levels for post-combustion carbon capture technologies.

³⁸ <https://netl.doe.gov/sites/default/files/event-proceedings/2017/co2%20capture/1-Monday/A-Bhown-EPRI-CO2-Capture-R-D-at-EPRI.pdf>

³⁹ <https://www.bakerhughes.com/process-solutions/chilled-ammonia-process>

Table 28. *Technology Readiness Levels of Carbon Capture Technologies (Akpasi and Isa 2022; Koytsoumpa et al. 2021)*

Technology	TRL Level
Adsorption	9 for amine systems 7 for chilled ammonia
Absorption	9
Membrane	6-7
Cryogenic	5
Calcium looping	6-7

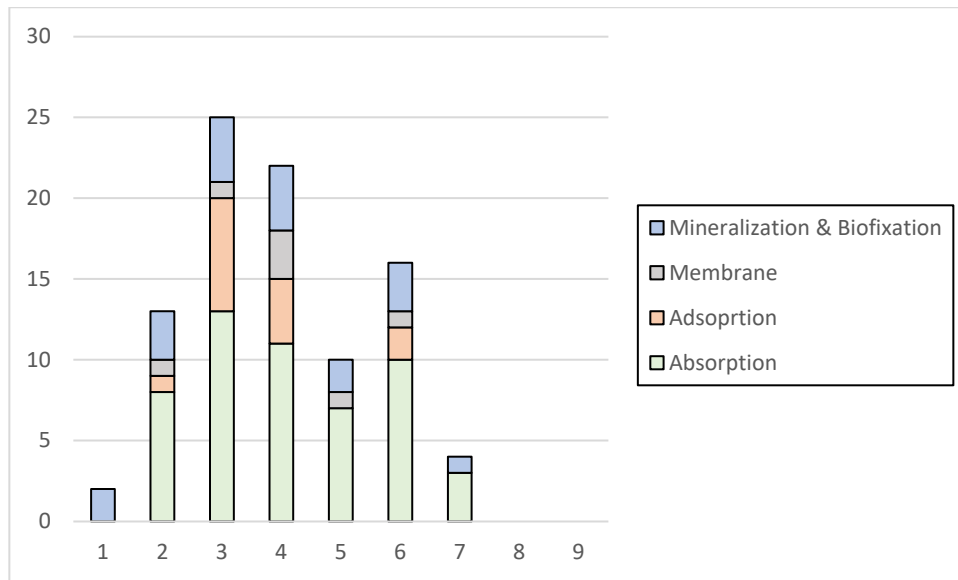


Figure 38. *TRL Distribution of Ninety-Two Post-Combustion CO₂ Capture Processes (Freeman and Brown 2011)*

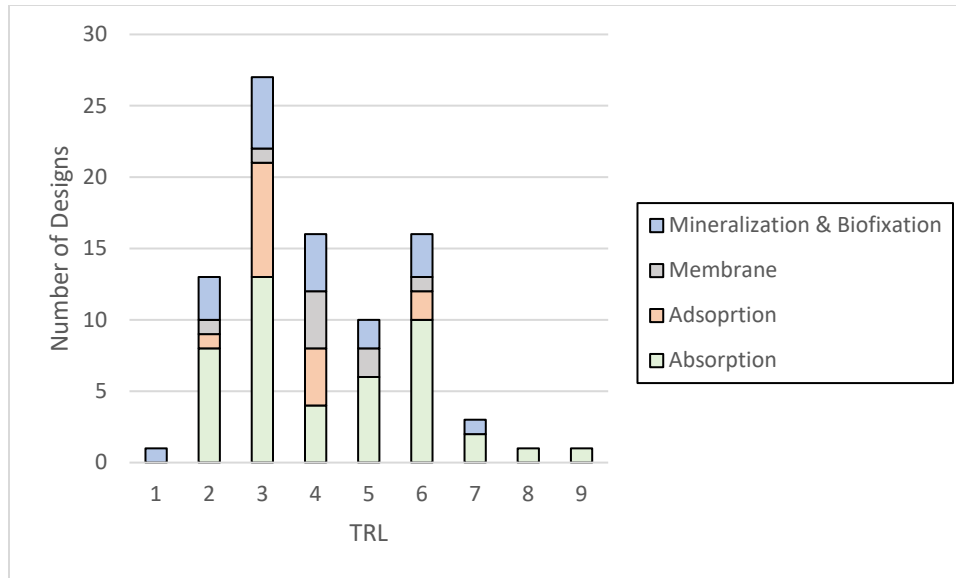


Figure 39. TRL Distribution of Eighty-Eight Post-Combustion CO₂ Capture Processes in 2016³⁸

6.9 Bioenergy Carbon Capture

Bioenergy carbon capture applies carbon capture techniques to a biomass energy source. Due to the inherent differences in carbon between biomass-based combustion and fossil-based combustion⁴⁰, bioenergy carbon capture has the potential to be a net negative approach, i.e., total carbon footprint of operation is less than zero if the biogenic CO₂ is captured or utilized. This approach is often referred to as bioenergy carbon capture and storage and/or use (BECCS/U). Effective overviews of bioenergy with carbon capture and storage (BECCS) technology include the reviews by Tanzer et al. (2021) and Koytsoumpa et al. (2021). In addition, Sagues et al. (2020) examined the industry wide implications of post-combustion amine-based carbon capture applied to the US pulp and paper sector.

Importantly, some studies have estimated that energy demand of full CO₂ capture can switch paper mills from being net energy exporters to energy importers (Santos et al. 2021) or require supplemental fuel (Sagues et al. 2020; Onarheim et al. 2017a). If only on-site energy is used, estimates of capturable CO₂ ranged from less than 30% (Sagues et al. (2020) and Kuparinen et al. (2019; 2020; 2022)) to 90% (with an 80% reduction in electricity exports) (Onarheim et al. 2017a).

Bioenergy Carbon Capture Projects Pertinent to the Forest Products Industry

Drax

Drax Group is a renewable energy company generating renewable power from the production and utilization of sustainable biomass. Drax owns and/or has financial interest in 17 pellet mills in the US South and Western Canada, with a total capacity to manufacture 4.9 million metric tons of compressed wood pellets per year. The pellets are produced using wood fiber and are supplied to third-party customers in Europe and Asia for the generation of renewable power. Drax’s pellet mills supply around 20% of the biomass used at its own power station in North Yorkshire, England. Drax and Mitsubishi

⁴⁰ <https://www.ncasi.org/resource/biomass-carbon-cycle-diagram/>

Heavy Industries (MHI) have partnered to develop a bioenergy with carbon capture and storage (BECCS) pilot facility at Drax Power Station in North Yorkshire, England⁴¹. MHI's 12-month pilot test will capture approximately 300 kg of CO₂ a day for the purpose of confirming the compatibility of MHI's technology with biomass combustion flue gases at Drax. MHI's technology is a post-combustion amine-based process using a proprietary amine base solvent called KS-21™ (see Figure 40). Compared to MHI's KS-1™ solvent, which is used at 13 commercial carbon capture plants globally, KS-21™ is reported to have several advantageous properties such as lower volatility and greater stability against degradation. Drax and MHI have signed a long-term agreement for utilization of MHI's carbon capture technology⁴².

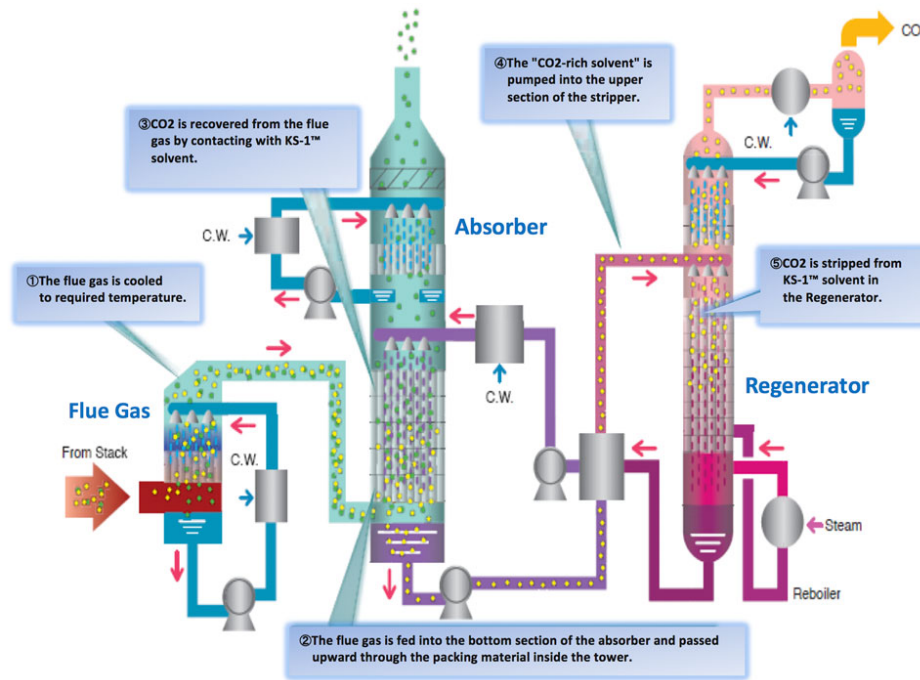


Figure 40. MHI's Post-Combustion Amine-Based Carbon Capture System Being Used at Drax Power Station in North Yorkshire, England

Drax recently announced they have been invited to enter formal bilateral discussions with the English Government to move the bioenergy carbon capture project forward and ensure the Government is able to fulfill its restated commitment to achieving 5 million metric tons per year of engineered Greenhouse Gas Removals (GGRs) by 2030.⁴³

⁴¹ https://www.drax.com/press_release/negative-emissions-pioneer-drax-and-leading-global-carbon-capture-company-mitsubishi-heavy-industries-group-announce-new-beccs-pilot/

⁴² https://www.drax.com/press_release/drax-and-mitsubishi-heavy-industries-sign-pioneering-deal-to-deliver-the-worlds-largest-carbon-capture-power-project/

⁴³ <https://www.drax.com/investors/drax-enters-formal-discussions-with-uk-government-on-large-scale-power-beccs/>

Resolute

The Resolute pulp and paper mill in Saint-Félicien Québec started up a CO₂ capture unit on March 14, 2019⁴⁴. The \$7.4 million (CAD\$) project involves the capture of up to 30 metric tons of CO₂/day from the softwood kraft pulp mill, the majority of which is piped to the Serres Toundra’s vegetable greenhouse adjacent to the mill (see Figure 41). The carbon capture technology is enzymatic-based to enhance the CO₂ capture rate⁴⁵.



Figure 41. Resolute Saint-Félicien Pulp Mill and Serres Toundra’s Vegetable Greenhouse

INCE Bio Power

The Bioenergy Infrastructure Group (BIG) operates and manages the Ince Bio Power Plant, which is the largest waste wood gasification plant in the UK. The INCE carbon capture project, known as Ince Bioenergy Carbon Capture and Storage (InBECCS) entered phase 2 in 2022⁴⁶. Phase 1 of the project was the design and feasibility study of the CCS facility. Phase 2 of the InBECCS project will demonstrate the

⁴⁴ <https://www.pulpandpapercanada.com/co2-capture-unit-starts-up-at-resolutes-saint-felicien-pulp-mill-1100001622/>

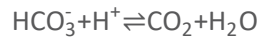
⁴⁵ https://s3.ca-central-1.amazonaws.com/medias.bba.ca/documents/pdf/BBA_Case-Study_-CO2-capture-at-Saint-Felicien_EN.pdf

⁴⁶ <https://c-capture.co.uk/c-capture-partners-in-ince-bio-power-carbon-capture-demonstration-project-which-secures-funding-in-win-for-net-zero-ambitions-in-north-west/>

ability to capture over 7,000 metric tons of carbon per year. BIG is targeting 2027 or earlier for the commercial scale CCS plant to be operational.

6.10 Enzyme Enhancement

Carbonic anhydrase (CA) is the fastest known enzyme in nature. It catalyzes bicarbonate to CO₂ via the reaction:



The CA enzyme has been demonstrated to catalyze the reversible CO₂ hydration reaction to form bicarbonate under typical conditions found in industrial flue gases (Bond et al. 2001). The CA enzyme can also be used synergistically with amine-based scrubbing systems to accelerate the CO₂ reaction absorption rate (Gladis et al. 2019). Current research has focused upon improving thermal and alkali stability and halotolerance of CA enzymes. Maciel et al. (2022) provide an effective summary of work done around CA improvements and studies of CO₂ absorption with amine-based solvents and CA. In all the studies cited, CA improved the amine absorption rate between 1.2-25-fold compared to systems without CA. Much of the work on CA enzyme enhancement is at the lab- to bench-scale (~TRL 4).

6.11 Storage and Transport of CO₂

Pipelines are the primary mode of transport for CO₂ and have been deployed for enhanced oil recovery (EOR) (Orr 2018). Requirements for pipeline transport of CO₂ are temperatures of ~25°C and pressures at ~110 bar (Metz et al. 2005), which mean that most carbon capture technologies require a cooler and compressor at the tail end of the system. Purity requirements for final storage may also range from 95 to 99 mol%, depending on the storage site (Pipitone and Bolland 2009). Carbon capture technologies that do not meet purity requirements would require a CO₂ purification unit as an add-on prior to pipeline injection. Options for long-term storage include underground geological storage, deep ocean storage, and EOR (Metz et al. 2005). McKinsey provided a recent map of potential sink locations and associated capacity within the United States. High-capacity storage regions do overlap with pulp and paper production in the Southeast and in the Pacific Northwest.

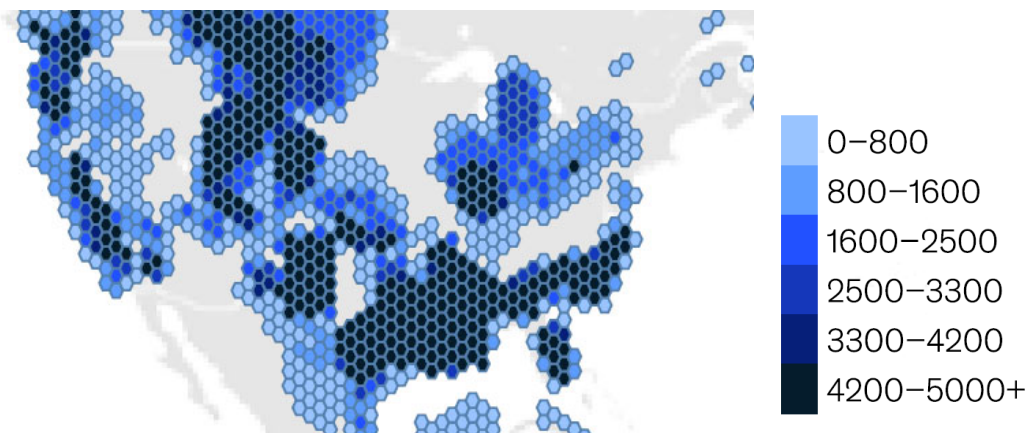


Figure 42. US Map of Potential Sink Locations and Capacity (McKinsey 2023)⁴⁷

⁴⁷ <https://www.mckinsey.com/industries/oil-and-gas/our-insights/the-world-needs-to-capture-use-and-store-gigatons-of-co2-where-and-how#/>

7.0 Electrification of Heat

Electrification of heat has been promoted as one of the pathways to achieve decarbonization in difficult-to-decarbonize sectors such as manufacturing (McKinsey & Company 2018; RVO 2017). Electrification of heat is the substitution of industrial process heat sources with zero or low-carbon electricity to generate heat. The global pulp and paper sector, which consumed approximately 7 exajoules of energy (70% from fuel sources used to generate heat)⁴⁸, has been one of the sectors considered for electrification efforts (McKinsey & Company 2018). The general approach to electrification is to either replace the energy generation device (steam generating boiler) within the mill with an electric equivalent or to replace process operations that consume steam within the mill with an electric equivalent. Both opportunities are reviewed below.

Most pulp and paper operations in the United States have high thermal loads expressed as percentage of total fenceline energy needs (see Table 29). In chemical pulp and paper mills, for example, thermal demand (in the form of steam) represents 75-90% of total fenceline energy needs. Because of the large thermal loads and the use of primarily biomass residuals and biomass by-products (black liquor) at chemical pulping mills, electrification of process heat may not be economically feasible or ecologically desirable.

Table 29. Fenceline Thermal Loads for Pulp and Paper Operations

Mill Type	Fenceline Energy Needs that are Thermal	Production Representation in the US ¹
Bleached kraft market pulp	80-88%	12%
Bleached kraft ²	75-85%	13%
Unbleached kraft	78-86%	26%
Non-deinked	70-75%	33%
Deinked	40-60%	4%
Non-integrated	50-75%	7%
Mechanical	2-10%	2%

¹ About 4% of the pulp production in the US is from other pulping types such as sulfite, NSSC, soda, etc.

² Integrated bleached kraft mills

Chemical pulp mills have large onsite steam demands for driving several unit processes needed to manufacture product and to efficiently generate steam and electricity in combined heat and power systems. Figure 43 shows the typical steam properties and uses at a chemical pulp mill. Mills use low-pressure and medium-pressure steam for process needs, intermediate steam for sootblowing purposes, and high-pressure steam for electricity generation.

⁴⁸ <https://www.iea.org/reports/pulp-and-paper-2>

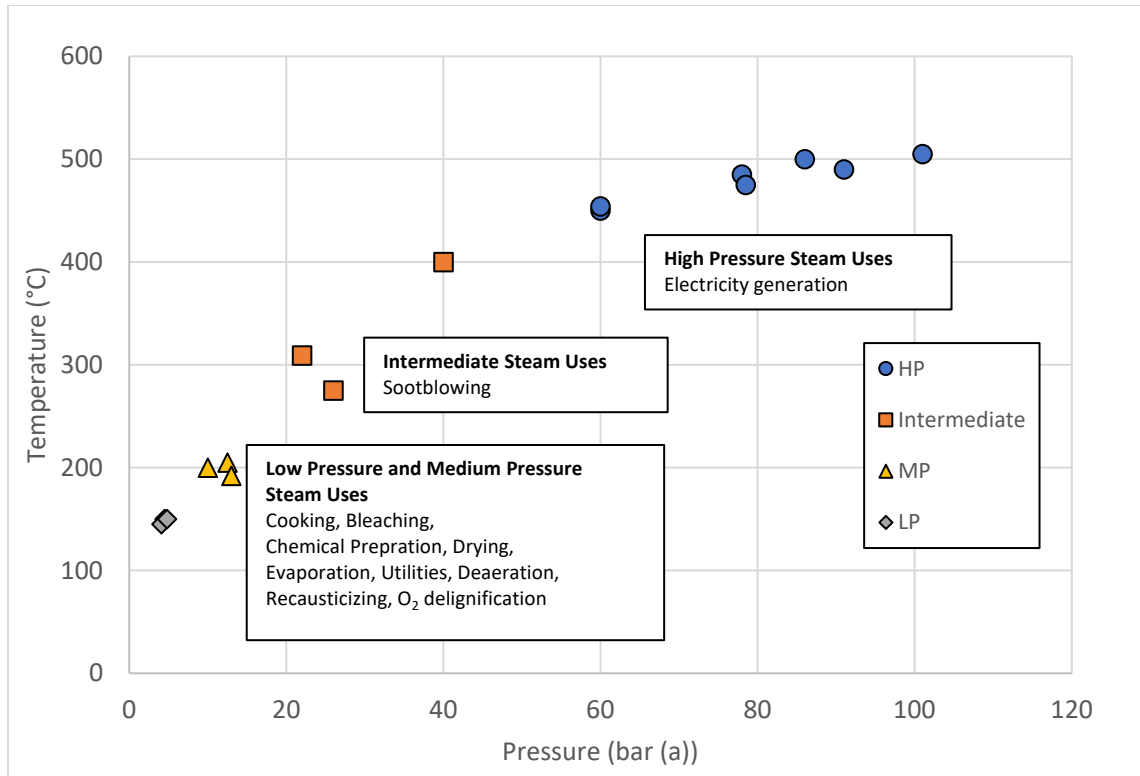


Figure 43. Typical Steam Properties and Uses at Chemical Pulp Mills (compilation of numerous sources)

The GHG benefits of electrification of heat assume that fossil fuels used for steam generation are being displaced by zero carbon electricity⁴⁹ such as hydro-electric, nuclear, solar, or wind for steam generation (McKinsey & Company 2018). The US pulp and paper industry generates steam and electricity via predominantly low greenhouse gas (GHG) and energy efficient combined heat and power (CHP) systems. Combined heat and power is the simultaneous generation of steam and electricity (see the section on CHPS in the US forest products sector in the section on Background on the US forest products sector). In the United States, 95.4% of onsite electricity production at pulp and paper facilities is generated via CHP. Due to the energy efficient nature of CHP, the US pulp and paper sector avoids over 12 million metric tons of CO₂e annually by using CHP compared to the separate generation of steam and electricity. CHP systems provide resiliency benefits to the electricity grid and the avoidance of transmission and distribution losses by consuming power at the point of generation. The benefits of energy generation from CHP for the pulp and paper sector would be lost by transfer of onsite energy generation to distributed electricity systems for steam generation.

Approximately two-thirds of US pulp and paper energy needs are met with carbon neutral biomass and other renewables (EIA 2021)⁵⁰. Utilization of biomass is cited by McKinsey & Company (2018) as an often

⁴⁹ It is important to note that even in 2050 the US grid will not be entirely based upon zero carbon electricity. The average US grid emission factor is projected to be 264 kg CO₂e/MWh in 2050 (EIA Annual Energy Outlook 2022 with 2050 projections).

⁵⁰ EIA MECS 2018 Fuel Consumption. February 2021.

https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table3_2.pdf

lower cost alternative to electrification of heat. The primary source of biomass energy for the US pulp and paper sector is spent liquor solids, a by-product of the kraft pulping process. The kraft recovery system is designed to not only generate energy from spent pulping liquor solids, but to recover pulping chemicals and manage black liquor solids, and these important functions of the kraft recovery system are not addressed by the electrification of heat. The GHG benefits attributable to the recovery of pulping chemicals are equivalent to the total Scope 1 and 2 emissions from the entire US pulp and paper industry (Gaudreault et al. 2012).

Most of the fossil fuel fraction currently being used within the pulp and paper sector (primarily natural gas) is non-switchable to other forms of energy. In 2018, the US Paper Sector (as defined by North American Industrial Classification System (NAICS) 322) reported using 551 billion cubic feet of natural gas for energy generation. Of this amount, 489 billion cubic feet, or 88.4% of consumption, was considered not switchable to another fuel source⁵¹. The main reason cited within the EIA MECS survey for the inability to switch from natural gas was that the installed equipment is not capable of using another fuel (344 billion cubic feet or 70% of the non-switchable total)⁵². Other major reasons listed include environmental restrictions (31 billion cubic feet or 6% of the non-switchable total), unavailable alternative fuel supply (15 billion cubic feet or 3% of the non-switchable total), and long-term contracts in place (8 billion cubic feet or 1.6% of the non-switchable total). In 2018, the US Wood Products Sector (as defined by NAICS 321) reported consuming 65 billion cubic feet of natural gas. Of this amount, 63 billion cubic feet, or 97% of consumption, was considered not switchable to another fuel source. The capability of US manufacturers to switch from natural gas has been declining since 1994⁵³.

7.1 Electric Boilers

Electric boilers typically use electric-powered resistive heating elements to convert electricity to heat. Larger capacity electric boilers are typically electrode boilers (jet type) that use electricity flowing through streams of water to create steam (Hasanbeigi et al. 2021). The pulp and paper sector generates high temperature and high pressure superheated steam for generation of electricity and process steam in efficient combined heat and power systems (NCASI 2019a). Commercially available electrode boilers with capacities of up to 70 MWe are available, but only generate saturated steam up to 350°C (RVO 2017). Superheated steam generation in the temperature range of 450-525°C is more typical of steam generation within the pulp and paper sector (NCASI 2019b). The manufacturer PARAT IEH markets a high voltage boiler for producing steam and hot water⁵⁴. High pressure steam of up to 85 bar gauge (saturated temperature) and up to 75 MW (256 MMBtuh/hr) can be produced. Super-heated steam can be delivered separately with a low-voltage supply. Figure 44 shows a schematic of a PARAT IEH electrode boiler and hot water system. UPM announced the purchase of eight electric boilers for replacement of fossil fuel boilers within some of their mills in Finland and Germany⁵⁵. The UPM

⁵¹ Table 10.2 Capability to Switch Natural Gas to Alternative Energy Sources, https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table10_2.pdf

⁵² Table 10.21 Reasons that Made Natural Gas Unswitchable, https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table10_21.pdf

⁵³ <https://www.eia.gov/todayinenergy/detail.php?id=37292>

⁵⁴ <https://www.parat.no/en/products/industry/parat-ieh-high-voltage-electrode-boiler/>

⁵⁵ <https://www.upm.com/about-us/for-media/releases/2023/04/upm-electrifies-heat-and-steam-production-at-its-mills-in-finland-and-germany/>

Tervasaari paper mill has commissioned a 50 MW electric boiler, and a new, more efficient 60 MW electric boiler will also be installed at the mill. The new boiler will produce steam and heat for the mill and heat for the Valkeakoski district heating network.

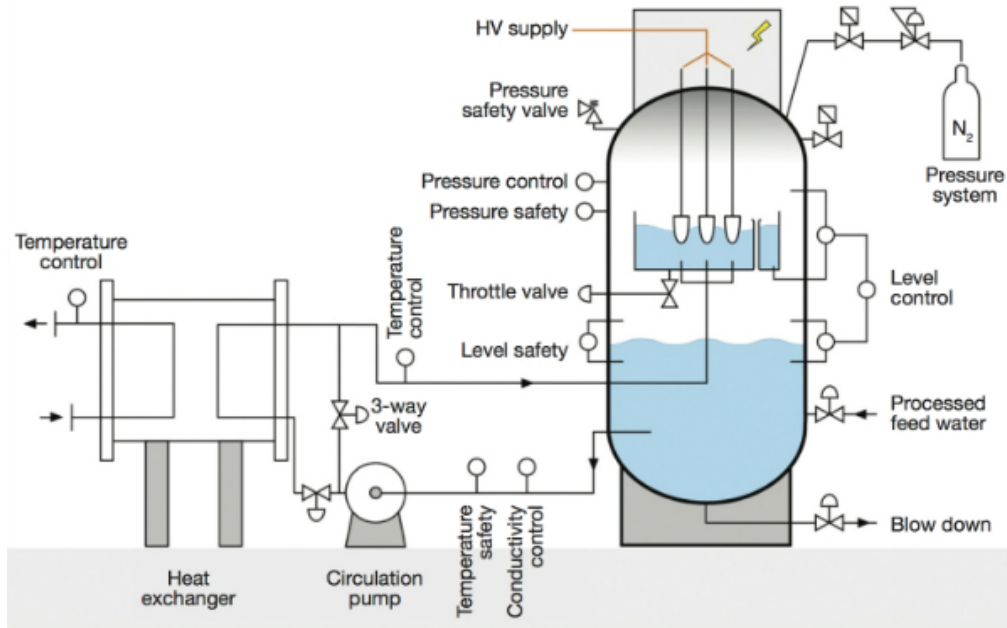


Figure 44. Schematic of the PARAT IEH Electrode Boiler and Hot Water System

The electrification of boilers is touted as a cross-cutting industrial opportunity for greenhouse gas reductions in the industrial sector (Schoenberger et al. 2022). The authors determined that boiler electrification may lead to decarbonization under a future, high renewables electric grid, but boiler electrification under current electric grid conditions leads to increases in GHG emissions of 105 MMmt CO₂e and 73 MMmt CO₂e with and without the replacement of by-product fuels (Schoenberger et al. 2022). The forest products industry is one of the largest users of by-product fuels in boiler operations (Jibran et al. 2021). Schoenberger et al. (2022) characterized the US industrial boiler fleet by integrating information from the US EPA Greenhouse Gas Reporting Program (US GHGRP), the Boiler Maximum Achievable Control Technology (MACT) emissions and survey database, and the National Emission Inventory (NEI) (2022). Large boilers (capacity >250 MMBtu/hr) represent 77% of the energy demand in the forest products industry (Table 30).

Table 30. Annual Energy Demand by Forest Products Industry Boiler Capacity in 2018 (Schoenberger et al. 2022; Jibran et al. 2021)

Boiler Size		Energy Demand (PJ HHV)	Percent Representation
<2.9 MW	< 1.0 MMBtu/hr	3.1	1%
2.9-14.7 MW	10-50 MMBtu/hr	11.6	4%
14.7-29.3 MW	50-100 MMBtu/hr	10.4	3%
29.3-73.3 MW	100-250 MMBtu/hr	47.1	15%
>73.3 MW	>250 MMBtu/hr	247	77%

Using EIA MECS data (EIA 2021) and EIA manufacturing and energy carbon footprints (EERE 2021), Jibran et al. (2021) calculated the greenhouse gas implications of electrification of boilers within US manufacturing. Five industrial sectors consume over 90% of the boiler energy demand in the industrial sector and are ranked as follows: (1) chemicals 707 PJ HHV, (2) petroleum refining 490 PJ HHV, (3) food and beverage 359 PJ HHV, (4) forest products 326 PJ HHV, and (5) iron & steel 117 PJ HHV. All other US industrial sectors together consumed 204 PJ HHV in boiler operation (EIA 2021; Energetics 2019). Some industrial sectors have high percentages of “other” fuels reported within EIA MECS, e.g., “other” fuels represent ~65% of total boiler input for the forest products sector (Jibran et al. 2021). The “other” fuels GHG contributions were estimated by Jibran et al. (2021) for the major industrial sectors reporting other fuels (see Figure 45). Jibran et al. (2021) incorrectly assumed biogenic carbon dioxide emissions as equivalent to fossil-based emissions when developing the GHG contributions from “other” fuels reported through the EIA MECS survey, which negatively impacts the forest products industry due to its high percentage of biomass fuels (see Figure 46), and leads to overly optimistic conclusions for electrification potential for the forest products sector through boiler electrification. The forest products sector was calculated to contribute 35 MMmt CO₂e in savings from boiler electrification in 2050 (out of 195 MMmt CO₂e of the US industrial sector in 2050) (Jibran et al. 2021).

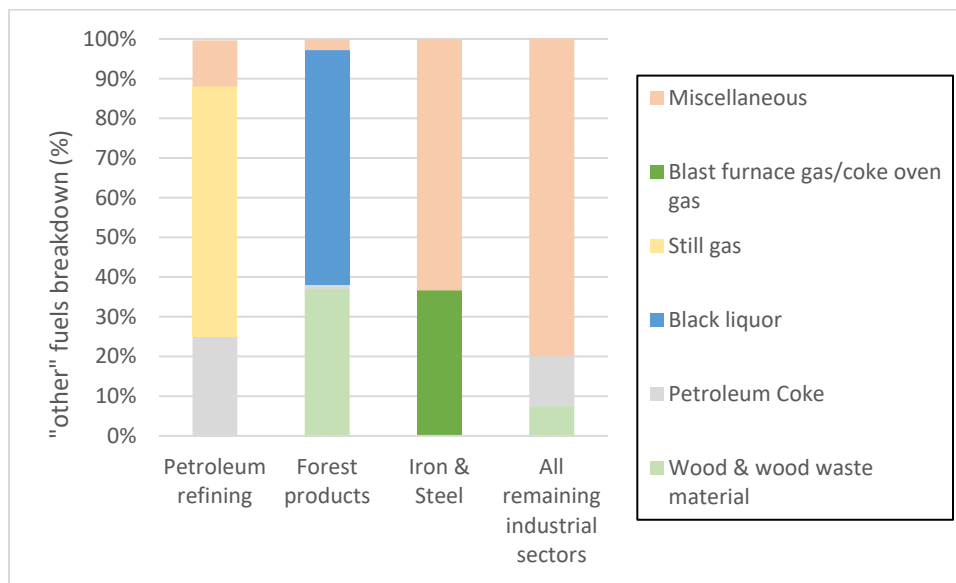


Figure 45. Distribution of "Other" Fuels Used in US Industrial Combustion Boilers (tCO₂/GJ) (Jibran et al. 2021)

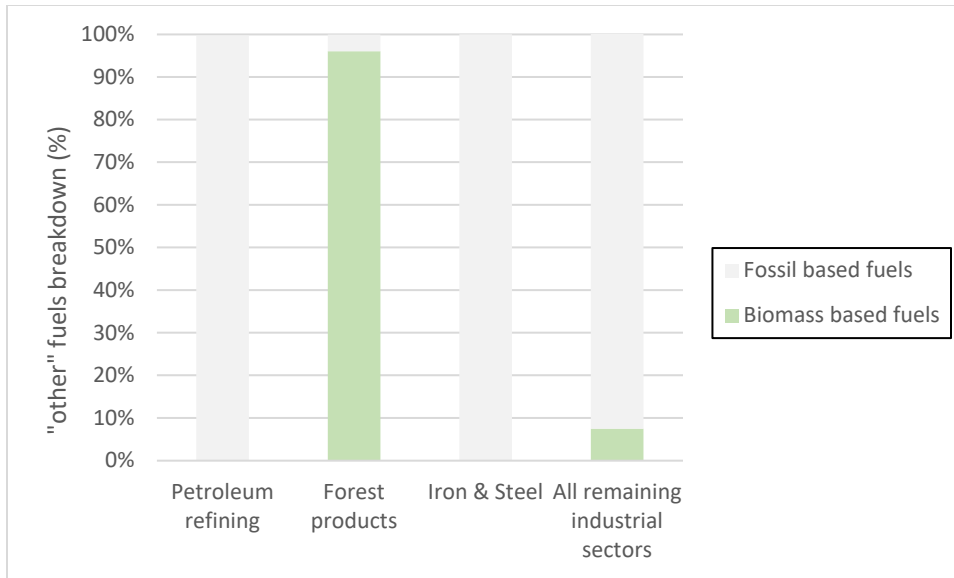


Figure 46. Distribution of "Other" Fuels Used in US Industrial Combustion Boilers (tCO₂/GJ) (adapted from Jibrán et al. 2021)

Jibrán et al. (2021) did acknowledge that the existence of low or no-cost by-product fuels in some industries such as refineries and forest products pose a great challenge to the electrification of by-product fuel boilers. Electrification of industrial boilers will also lead to significant additional costs for all industrial sectors, across all states, due to the large disparity between electricity and combustion fuel prices (Jibrán et al. 2022).

7.2 Infrared Drying of Paper

It is estimated that between 85 and 90% of paper and board produced is dried using the multi-cylinder design (Stenström 2020; Laurijssen and De Gram 2010). Other drying technologies include the Yankee dryer (4-5%, typically for tissue), infrared dryer (3-4%, coated paper), impingement dryer (2-3%, coated paper), and through dryer (1-2%, tissue) (Laurijssen and De Gram 2010). Multi-cylinder drying of paper is accomplished using steam as the driving force. Infrared radiation can be used to dry paper and is currently used for some coated paper applications. With infrared drying of paper, the paper passes through alternate sections of infrared radiation and cool-down. The principle behind this approach is presented in Figure 47. Humid air is exchanged with dry air via fans in the cool down sections. If powered by low or zero emission electricity, infrared drying can contribute to sector decarbonization.

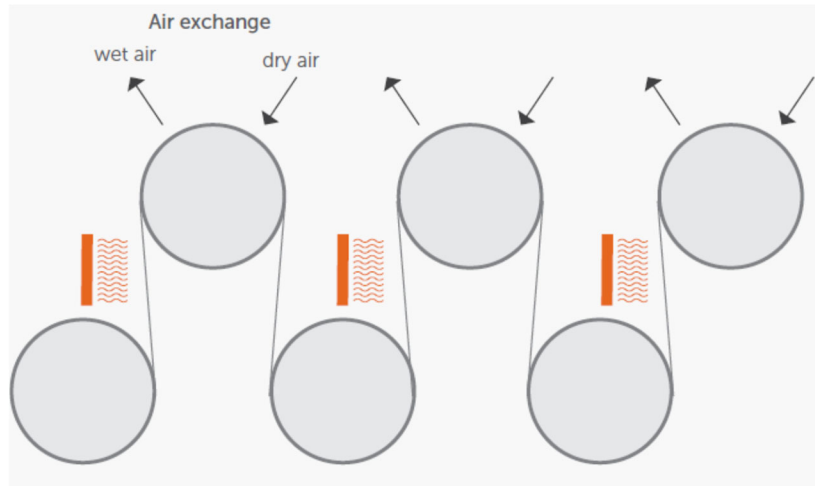


Figure 47. *Infrared Heating for Paper Drying (Beyond Zero Emissions 2018)*

Infrared drying systems have been limited to systems using natural gas (due to cost and operability constraints). They produce long wavelengths, limiting the application of this technology to drying coatings or providing additional drying capacity to cylinder drying⁵⁶. While electric infrared emitters generating short wavelengths and high-power densities have been developed, their adoption has been hindered by high operational and maintenance costs and limited service life (EPRI 1992).

Andritz has recently introduced its PrimeDry Hood E, which is an electrically heated hood for tissue machines (see Figure 48). Voith has a qDry Pro non-contact dryer (currently running on natural gas) (see Figure 49), that can be used in a number of different configurations for paper drying (see Figure 50). It is not known how many of these installations are in place at facilities.

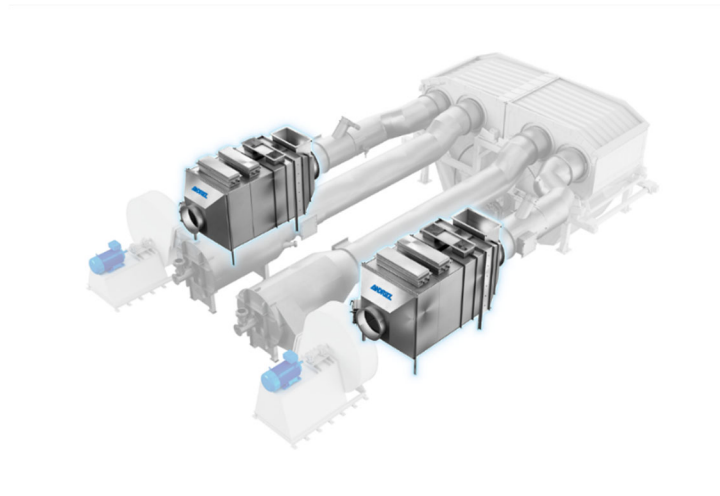


Figure 48. *Andritz PrimeDry Hood E Electrically Heated Hood for Tissue Machines*

⁵⁶ <https://www.coprocess.ca/short-wave-infrared->

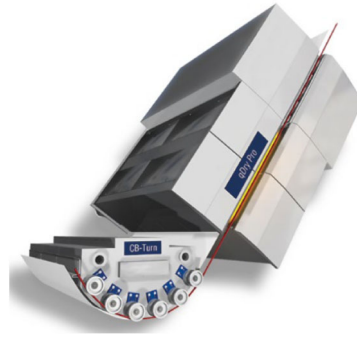


Figure 49. Voith qDry Pro Non-Contact Dryer⁵⁷

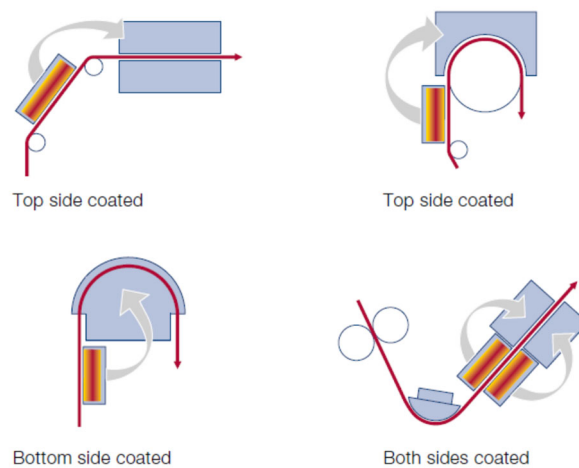


Figure 50. Voith qDry Pro Non-Contact Dryer Available Configurations⁵⁷

7.3 Industrial Heat Pumps

Waste heat utilization through heat pumps powered by low GHG electricity is one technique to decarbonize industrial energy use (Marina et al. 2021). Industrial heat pumps (IHPs) can reduce a site’s carbon footprint by (Rightor et al. 2022):

- Reusing recovered waste heat
- Electrifying process heat (if the GHG properties of the electricity are lower than those of the fuels used for generating process heat)
- Improving efficiency (current generation IHPs are more electricity-efficient and can be deployed locally, avoiding steam distribution systems)

⁵⁷ Voith Non-contact drying and web guiding
<https://d2euiryrvxi8z1.cloudfront.net/asset/445934742530/d828e2fdf22d9bc8e290e4bba8ae4db1/vp1113-english.pdf>

The heat pump operation is designed to upgrade low-grade heat (Q_w) at waste heat temperatures (T_w) to high grade, usable heat (Q_p) at process temperatures (T_p), i.e., a heat pump transfers heat from a low-temperature source to a higher-temperature sink. Electric power input is used to upgrade the heat (steam can be used as the IHP driver as well). A schematic of the electric heat pump principle is given in Figure 51. The difference between waste heat temperature (T_w) and upgraded process temperature (T_p) is typically referred to as the lift temperature.

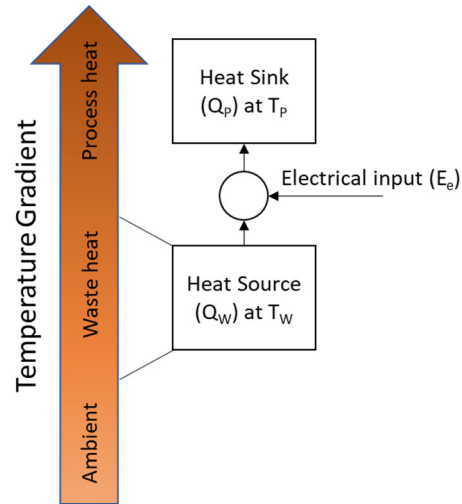


Figure 51. Thermodynamic Representation of Industrial Heat Pump

The efficiency of a heat pump is expressed with a coefficient of performance (COP), or seasonal coefficient of performance (SCOP). The higher the number, the more efficient and less energy consumptive the heat pump. COP is defined as the ratio of the heat transferred from a lower temperature reservoir to higher temperature reservoir divided by the required work input, which is equivalent to the electrical input for electrically driven heat pumps. Comprehensive overviews of IHPs are provided in Aspagaus et al. (2018) and Rightor et al. (2022).

Industrial heat pump adoption has been limited within the industrial sector due to cost and the achievable heat sink temperature for the heat pump. Several commercial models of heat pumps supply heat up to 90°C, which is not sufficient for many industrial applications (Aspagaus et al. 2018). Several types of commercially available electrically powered IHPs can provide process heat at up to 160°C (320°F) to replace much of the fossil fuels used in thousands of industrial operations. More advanced heat pumps that can supply heat up to 280°C (536°F) are currently in development⁵⁸. Figure 52 shows the process heat demand for select US industrial sectors (Rightor et al. 2022). The temperature range of 60-200°C is currently being targeted by industrial heat pump manufacturers. Some industrial heat pump installations have been implemented in the pulp and paper sector (where they are typically referred to as mechanical vapor recompression or MVR). Andritz⁵⁹ and Valmet⁶⁰ offer MVR black liquor evaporators,

⁵⁸ <https://www.aceee.org/industrial-heat-pumps>

⁵⁹ <https://www.andritz.com/products-en/group/pulp-and-paper/pulp-production/kraft-pulp/evaporation-plants/mvr-evaporators>

⁶⁰ <https://www.valmet.com/pulp/chemical-recovery/evaporators/mvr-evaporators/>

for example. The key performance metric for determination of economic viability of IHPs is the electricity/fuel price ratio (Rightor et al. 2022).

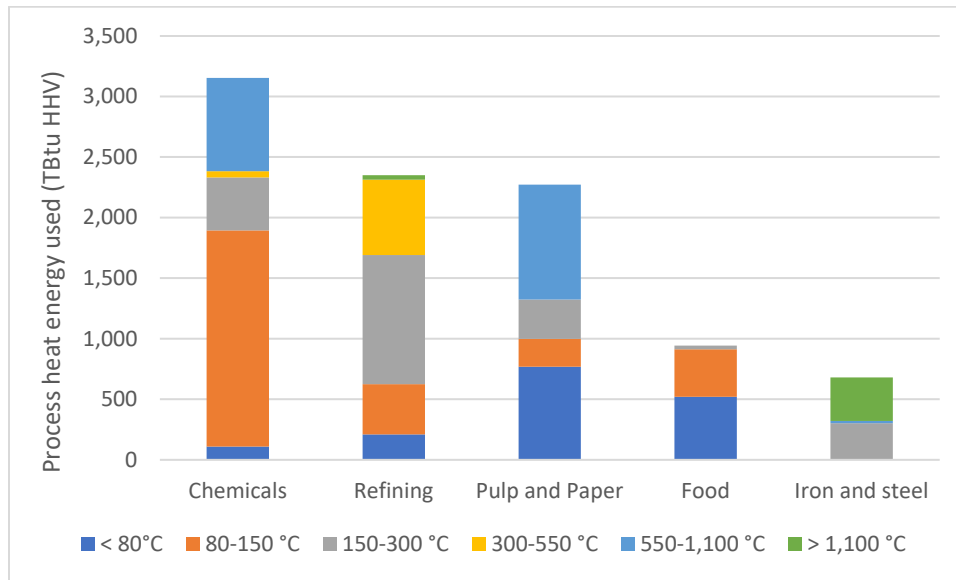


Figure 52. Process Heat Demand for Select Industrial Sectors in 2014 (Rightor et al. 2022; data from McMillian 2019)

In the work by Rightor et al. (2022), six types of IHPs were considered, each with various advantages, disadvantages, and technical readiness levels (see Table 31):

1. *Closed cycle mechanical vapor compression (MVC).* A completely closed refrigerant loop maintains the working fluid’s pressures and temperatures. A heat exchange is required on both the heat sink (condenser) and heat source (evaporator) sides.
2. *Semi-open cycle mechanical vapor recompression.* This IHP will typically take advantage of recompression waste low-pressure steam that would otherwise be vented or condensed with heat rejected to the ambient air.
3. *Open cycle mechanical vapor recompression.* The difference between the semi-open and open cycle is that a heat exchanger is used in the semi-open cycle to keep the waste vapors separate from the process steam or other heat exchange process vapors/liquids. In the open cycle, the (waste) vapors are reinjected directly back into the process without a separate heat exchanger.
4. *Open cycle thermal vapor recompression (TVR).* The TVR heat pump is perhaps the most common in industry today. It is the simplest as it has no moving parts, but it is restricted to compressing low-pressure (waste) steam (heat source) to a medium pressure steam header (heat sink) using high-pressure steam (IHP driver).
5. *Closed cycle heat activated Type 1.* The heat activated (HA) heat pump technology uses various chemical processes, such as absorption, adsorption, or a reversible chemical reaction, to transfer the heat from the source to the sink. In these systems the heat pump cycle is

predominantly heat activated. However, it does require a small amount of electricity for pumping the working fluid. The Type 1 design requires a supply of prime heat at an elevated temperature well above the heat sink temperature to enable it to lift the waste heat to the intermediate sink temperature.

6. *Closed cycle heat activated Type 2.* The Type 2 design is a waste-heat-driven heat pump where typically about one unit of heat is lifted to the higher sink temperature and one unit of heat is rejected to the ambient temperature. Type 2 designs require a sufficient temperature difference between the heat source and ambient, relative to the heat sink and source (life temperature).

Table 31. Industrial Heat Pump Types (Rightor et al. 2022)

IHP Type	Advantages	Disadvantages	TRL
Closed cycle MVC	<ul style="list-style-type: none"> • Good COP for moderate life temperature (<40°C) • Multiple vendors • Replace onsite steam or direct fired process heat 	<ul style="list-style-type: none"> • Requires low IHP life temperature and/or low electricity/natural gas price ratio (3-5) • Limited supply temperature to 160°C 	9
Open or semi-open cycle MVR	<ul style="list-style-type: none"> • Good COP for moderate life temperature (<40°C) • Electricity only on site • High volume flow compressor to compress steam • Can be combined with a closed cycle MVC 	<ul style="list-style-type: none"> • Requires low electric-fuel price ratio • High speed compressor 	9
Open cycle thermal vapor recompression	<ul style="list-style-type: none"> • Smallest capital cost of the different IHP types • Simplicity of operation (no moving parts) 	<ul style="list-style-type: none"> • Limited to steam as the working fluid • Limited to 20°C temperature lifts 	9
Closed cycle heat activated Type 1	<ul style="list-style-type: none"> • Uses lower cost fuel or steam as driver • Minimal moving parts • Higher supply temperature ~200°C 	<ul style="list-style-type: none"> • High CAPEX • Large footprint required • Limited vendors • Emerging technology 	4-7
Closed cycle heat activated (or sorption) Type 2	<ul style="list-style-type: none"> • Uses waste heat as driver • Minimal moving parts • High supply temperature ~200°C 	<ul style="list-style-type: none"> • High CAPEX • Large footprint required • Limited vendors • Emerging technology • Requires adequate temperature drop from waste heat to ambient 	4-7

7.4 Electric Lime Kiln

VTT (the Finnish Research Institute) has developed a pilot-scale electric-powered lime kiln (Figure 53) to test the concept of replacing fossil fuels in the lime kilns with electricity as the power source for the calcination reaction⁶¹. The kiln is 10 meters in length, has a capacity of 100 kg/hour (2.4 mtpd), and can deliver 300 kWe in power.



Figure 53. VTT's Electric Rotary Lime Kiln

7.5 Economics of Electrification of Heat

McKinsey & Company (2018) highlights that electrification of heat approaches are currently not cost competitive with conventional production technology. For producers of commodity products (such as the pulp and paper sector) cost is the decisive consideration in purchasing decisions. McKinsey & Company states that “companies that increase their production costs by adopting low-carbon processes and technologies will find themselves at an economic disadvantage to industrial producers that do not.”. The use of electricity for thermal energy generation is more expensive than the generation of thermal energy from fuels (see Figure 54) (CIBO 2019). Average industrial electricity costs, $\$_P$, can be found in EIA’s Electric Power Monthly⁶² and from EIA’s short term energy outlook⁶³. Pulpwood stumpage prices for the US Southeast can be taken from Timber-Mart South⁶⁴. Hasanbeigi et al. (2021) determined that, overall, the energy cost per unit of production in almost all cases analyzed is currently higher for electrified processes compared to conventional ones.

⁶¹ <https://www.vttresearch.com/en/ourservices/electric-rotary-kiln>

⁶² https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

⁶³ <https://www.eia.gov/outlooks/steo/tables/pdf/2tab.pdf>

⁶⁴ <http://timbermart-south.com/prices.html>

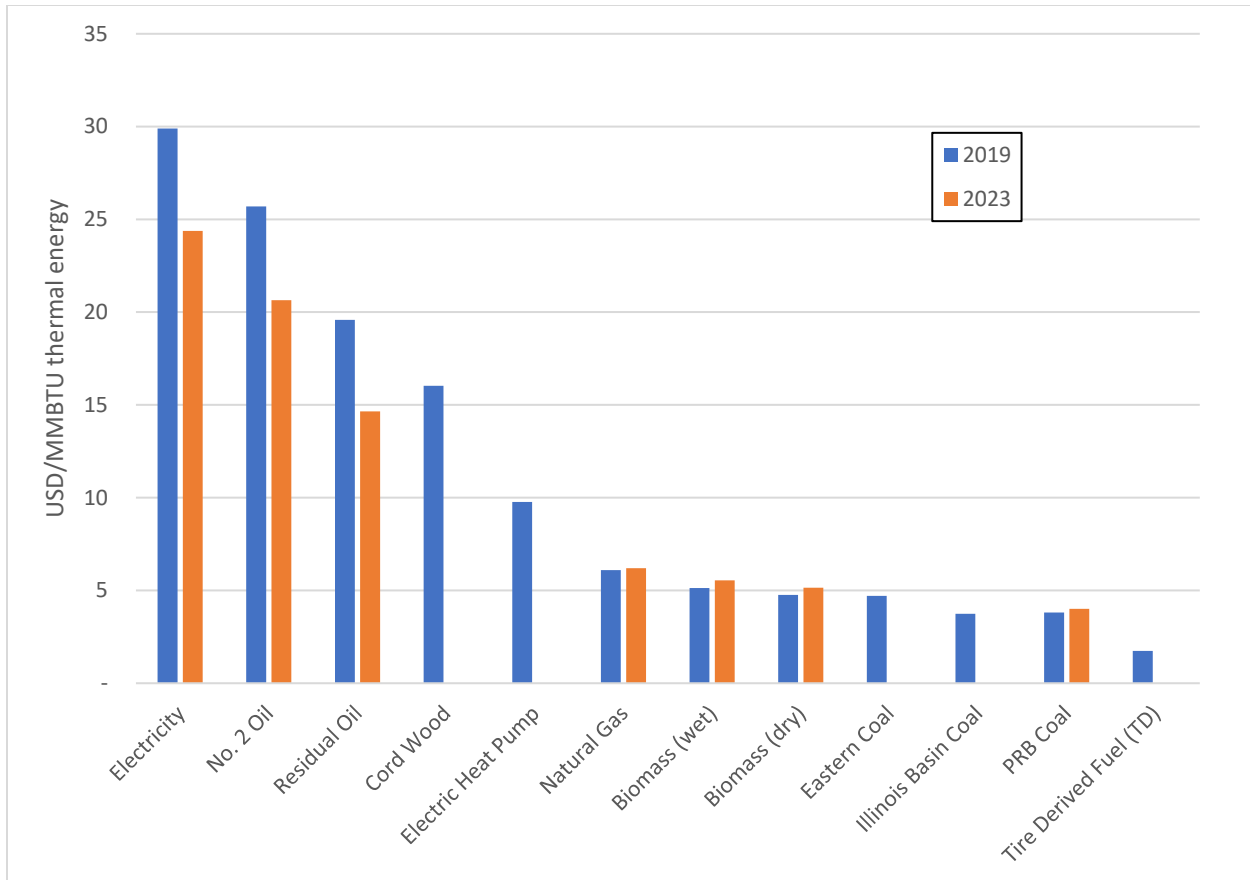


Figure 54. Thermal Generation Costs from Common Fuels
(CIBO 2019 and updated prices from EIA and Timber-Mart South⁶⁵)

McKinsey & Company (2018) listed several challenges associated with electrification of heat, all of which are applicable to the forest products industry:

- Emissions related to the process and feedstocks cannot be abated by a change in fuels, but only by changes to the process. Approximately 21% of natural gas and residual fuel oil used by the pulp and paper sector is process related.
- Retrofitting energy generation systems to alternative fuels such as zero-carbon electricity would require significant changes to the boiler and auxiliary power generation systems.
- Industrial processes are tightly integrated, and therefore, any change to one part of the process (such as parts of the steam and power generation system) must be accompanied by changes to other parts.
- Production facilities have long lifetimes, typically exceeding 50 years (with regular maintenance). Changing processes at existing sites requires costly rebuilds or retrofits.

⁶⁵ <http://timbermart-south.com/>

8.0 Policy Issues for Carbon Programs

Key features of carbon pricing policy to enable economic viability of surveyed technologies include:

- Placing a price on carbon.
- Recognizing the carbon neutrality of biomass residuals used for energy generation by the industry.
- Having energy intense trade exposed (EITE) treatment to reduce carbon costs of the fossil fuel fraction used by the industry.
- Providing carbon credits for negative emissions for sale or offsetting.

The European Union and Canada’s carbon markets have features of the first three bullets (NCASI 2020). NCASI has reviewed EITE methodologies and assessments for the forest products industry (NCASI 2019b) and has the NCASI Carbon Pricing Tool⁶⁶, a tool that aggregates and synthesizes key features of carbon cost programs worldwide.

The fourth carbon policy feature, providing carbon credits for negative emissions for sale or offsetting, is actively being developed in some jurisdictions. Sweden is pursuing reverse auctions⁶⁷ as an interim policy for incentivization of BECCS deployment to fulfill the fourth bullet (Lundberg and Fridahl 2022). Other policy options considered in Sweden for commercialization of BECCS include procurement auctions (essentially equivalent to reverse auctions); pre-determined uniform compensation⁶⁸ (Möllersten 2020) state guarantees; quota obligations⁶⁹; allowing participants in the EU ETS to use BECCS credits; private entities for voluntary compensation; and allowance of other states as buyers (Zetterberg et al. 2021). The United States currently does not have a nationwide carbon pricing program and is pursuing economic incentives such as the extension and modification of credits for carbon oxide sequestration within the Inflation Reduction Act (IRA)⁷⁰. Sagues et al. (2020) examined the prospects of BECCS in the US pulp and paper sector and the application of Section 45Q tax credits (pre-Inflation Reduction Act). A summary of the policy approaches considered for BECCS commercialization is provided in Table 32.

⁶⁶ <https://www.ncasi.org/resource/carbon-pricing-review-tool/>

⁶⁷ Reverse auctions: Auction where actors submit bids for selling their services to a buyer and the actor with the lowest bid wins.

⁶⁸ Pre-determined uniform compensation: A long term (fixed number of years) guaranteed compensation level for each verified carbon removal unit.

⁶⁹ With a quota obligation the state would require difficult to mitigate sectors to purchase BECCS credits corresponding to a share of their GHG emissions.

⁷⁰ Subtitle D – Energy Security, Sec. 13104. Extension and modification of credit for carbon oxide sequestration <https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf>

Table 32. Proposed Policy Approaches to Facilitate Adoption of Net Negative Technologies like BECCS
(from Möllersten 2020; Zetterberg et al. 2021; Sagues et al. 2020; Lundberg and Fridahl 2022)

Carbon Policy	Advantages	Disadvantages	Source
Pre-determined uniform compensation (State guarantees in Zetterberg et al. 2021 and 45Q carbon sequestration credits in the IRA and Sagues et al. 2020)	<ul style="list-style-type: none"> • Simple policy model. • Long-term security drives technological development. • Facilitates the entry of new players into the market. • Output based (per quantity of carbon captured) so provides incentive to maximize production. 	<ul style="list-style-type: none"> • Tariff setting and the adjustment process are challenging and complex, and finding the best compensation level for each country is difficult. • There is less control over the quantity of carbon units generated. Large budget spending when high deployment rates of carbon capture technologies are achieved. • When funded through a government budget the stability of the policy is linked to budget reliability. 	Möllersten 2020; Zetterberg et al. 2021; Sagues et al. 2020
Reverse auctions (Procurement auctions in Möllersten 2020)	<ul style="list-style-type: none"> • Considered compatible with EU state aid rules. • Guaranteed buyer for carbon removal units. • Long-term contracts with a fixed price per ton of captured and stored biogenic CO₂ provide auction winners with a stable investment horizon. • Incentivizes cost efficiency and price discovery through competitive bidding. • Limits can be set by the authorities for the quantity and the budget. • Competition results in cost-effectiveness and can provide price discovery of different technologies. 	<ul style="list-style-type: none"> • Discontinuous market development (stop and go cycles). • Difficult for bidding companies due to the high transaction costs (project proposals need planning, feasibility study, risk assessments) and the risk of not getting a return on investment in case a bid is not chosen. • High administrative costs. • High competition can lead to underbidding which tends to result in low financial returns. • Insufficient competition can lead to unjustifiably high bids. 	Lundberg and Fridahl 2022; Möllersten 2020

Quota obligation on difficult to decarbonize sectors	<ul style="list-style-type: none"> • Broadens the financing base for BECCS. • Reduced cost for the state. 	<ul style="list-style-type: none"> • Emission reductions from sectors that are difficult to decarbonize will lead to reduced revenue for BECCS. 	Zetterberg et al. 2021
BECCS credits for EU ETS	<ul style="list-style-type: none"> • Broadens the financing base for BECCS. • Could lead to significant demand for BECCS credits. • Eventually will bring down costs for participants in the EU ETS. 	<ul style="list-style-type: none"> • Would require major reform or amendment of the EU ETS Directive. 	Zetterberg et al. 2021
Expansion of voluntary markets to include BECCS	<ul style="list-style-type: none"> • Can contribute to deployment of BECCS. • Expands the demand base of the policy to include non-territorial carbon emissions. 	<ul style="list-style-type: none"> • States cannot count on emissions reductions. • Risk for double claiming of reduction units. 	Zetterberg et al. 2021
Other states as buyers		To prevent double counting, corresponding adjustments from national commitments would be required.	Zetterberg et al. 2021

Abdulla et al. (2021) examined the successfulness of CCS projects. Of the projects studied, more than 80% ended in commercial failure. Credibility of revenues and incentives were the most important attributes for project success or failure, as well as capital cost and technological readiness. Wang et al. (2021) analyzed 363 CCUS projects undertaken between 1995 and 2018. Larger projects (capacity greater than 1 Mt CO₂ captured/year) had failure rates 50% higher than smaller projects. The authors suggest gradual upscaling and increased policy support (particularly around demonstrations for the viability CCUS) are important steps to improve the viability of projects. The largest carbon capture and storage installation to date is the Petra Nova⁷¹ facility in Texas, which had the ability to capture 4,776 metric tons of CO₂ per day but has since been mothballed (IEEFA 2020). The Petra Nova facility was plagued with operating issues and low oil prices⁷². NRG Energy sold its 50 percent stake in Petra Nova for approximately US\$3.6 million, less than a half-percent of the roughly US\$1 billion in construction costs for the project. The US Department of Energy (DOE) provided US\$195 million in funding toward the project⁷³.

⁷¹ Petra Nova is one of two carbon capture and sequestration power plants in the world <https://www.eia.gov/todayinenergy/detail.php?id=33552>

⁷² <https://www.nenergybusiness.com/features/petra-nova-carbon-capture-project/>

⁷³ <https://ieefa.org/resources/ill-fated-petra-nova-ccs-project-nrg-energy-throws-towel>

9.0 Potential Effects on the Biomass Supply

Some of the decarbonation technologies such as biomass gasification to replace fossil fuel use in lime kilns and bioenergy carbon capture and storage will increase biomass utilization directly or indirectly because these technologies are energy intensive. The effect of bioenergy carbon capture on regional biomass supplies has been studied within Sweden and focused upon increased demand for logging residues to supply the additional heat demand for the carbon capture systems (Karlsson et al. 2021). Figure 55 shows the statistical distribution of US pulp mill biogenic CO₂ emissions. Pulp and paper mills emitting greater than 1 million metric tons of biogenic CO₂ annually are potential point source targets for deployment of net negative decarbonization technologies.

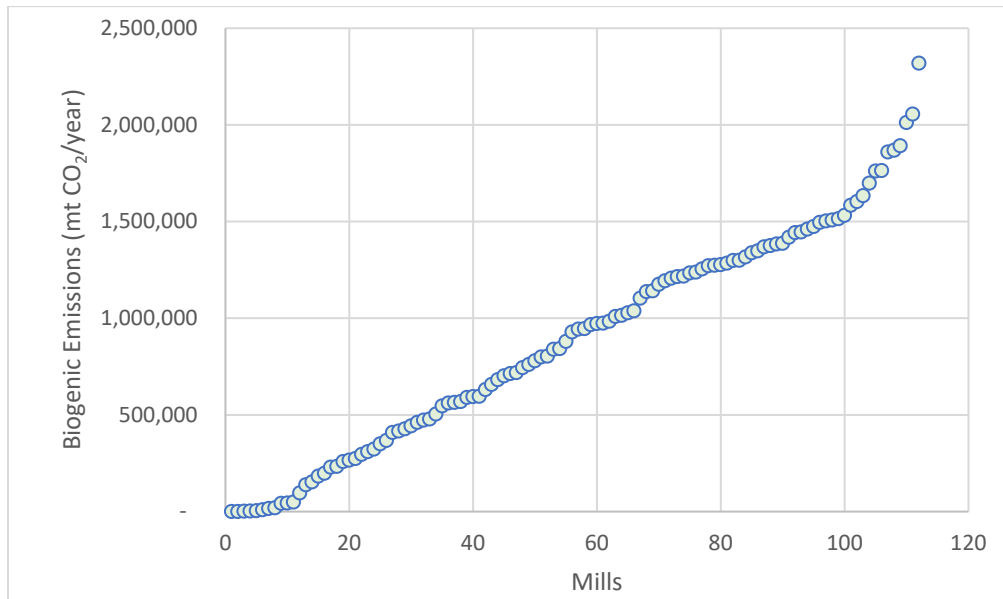


Figure 55. 2021 Biogenic CO₂ Emissions from US Pulp and Paper Facilities (US EPA GHGRP)

There are 50 pulp and paper mills in the US that emit greater than 1 million mt of biogenic emissions annually (Table 33). Figure 56 shows the geographic distribution of pulp and paper mill biogenic CO₂ emissions. Biogenic CO₂ emissions from the pulp and paper sector are focused within the Southeast, which has the largest concentration of chemical pulp mills. NCASI has examined trends in forest harvest and regeneration in the Southeastern⁷⁴ United States (NCASI 2022). In the Southeastern United States, approximately 276 million metric green tons (304 million short green tons) of forest products were produced in 2021 (see Figure 57).

⁷⁴ Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia

Table 33. *Biogenic CO₂ Emission Statistics for US Pulp and Paper Mills*

Statistic	Value (metric tons)
Average	893,391
Median	936,374
Minimum	278
Maximum	2,318,801
Total number of mills	112
Number of mills > 1 million	50

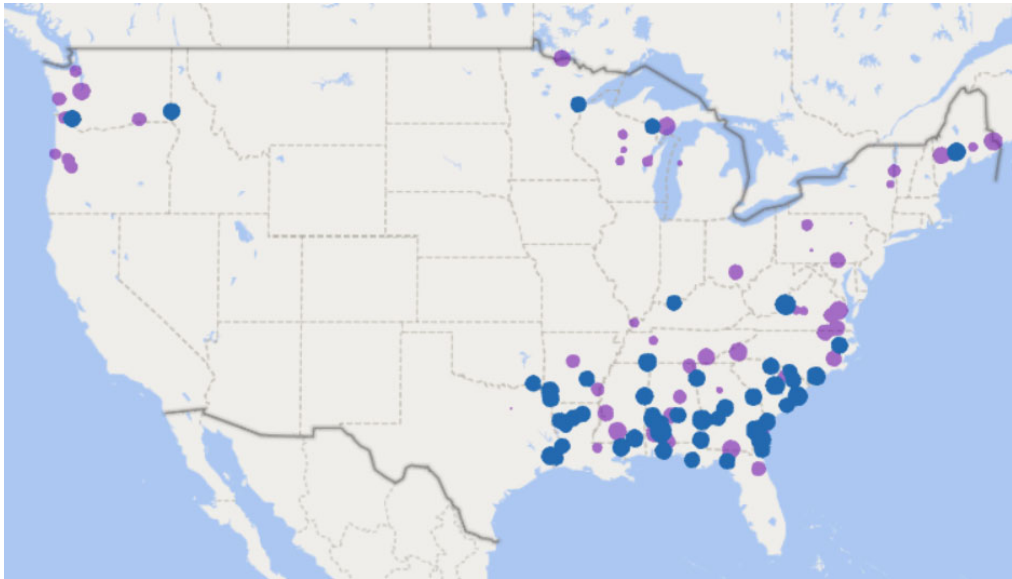


Figure 56. *US Pulp and Paper Mills with Biogenic CO₂ Emissions (blue circles are facilities emitting greater than one million metric tons annually)*

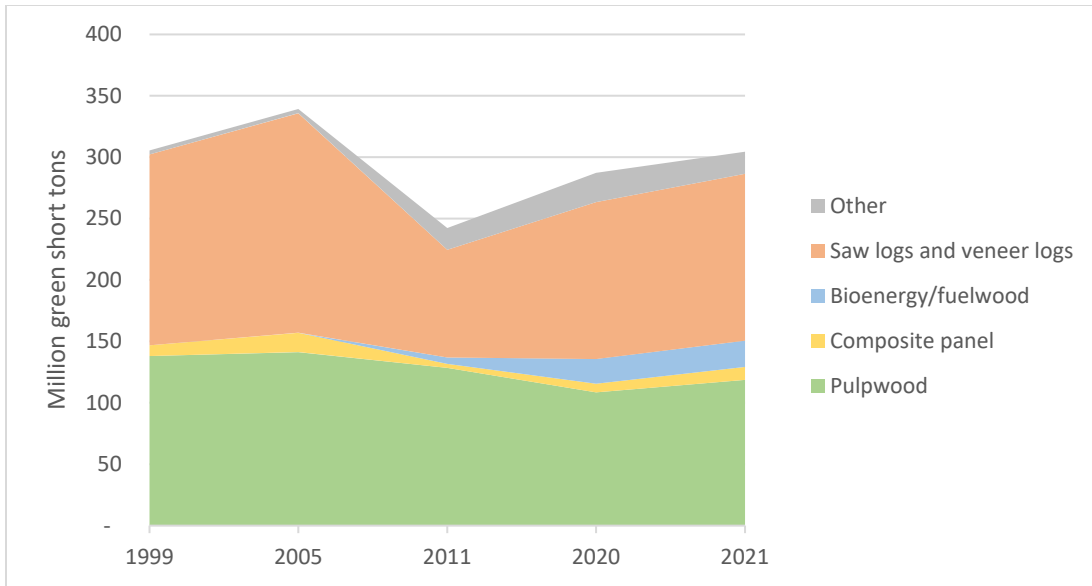


Figure 57. *Production of Forest Products in the Southeastern United States Over Time*⁷⁵

Table 34 provides summary results from the assessment of lime kiln biomass gasification installations, bioenergy carbon capture adoption, and the effect on available biomass supply at the state level⁷⁶. With 100% biomass gasification adoption at chemical pulp mills and approximately a one third adoption rate for carbon capture with MEA, the US pulp and paper sector in the studied states together could attain net zero status. Additional Scope 2 emissions of approximately 2.5 million mt CO₂e related to the increased electricity needs for biomass gasification in lime kiln and parasitic electricity needs for carbon capture would be required, which are offset by higher percentages of carbon capture. Utilization of approximately 5% of the currently available biomass supplies for generation of the thermal energy needs for biomass gasification and carbon capture would also be required.

⁷⁵ <https://public.tableau.com/views/TPOREPORTINGTOOL/MakeSelection?:showVizHome=no>

⁷⁶ For all US states that have at least one pulp and paper mill emitting greater than one million metric ton of biogenic CO₂ emissions annually

Table 34. State Level Calculations for Lime Kiln Biomass Gasification, Bioenergy Carbon Capture Adoption, and Effect on Available Biomass Supplies to Achieve Net Zero Operation (Balancing of Combustion and Process GHG Emissions)
 (In these calculations CCS adoption % is varied to offset US EPA reported GHG emissions and the additional emissions associated with increased electricity use in lime kiln biomass gasification and carbon capture with MEA.)

State	From US EPA GHG reporting			Lime Kilns		Carbon Capture with MEA			Available biomass consumed
	GHG emissions from combustion and process mt CO ₂ e	Lime kiln GHG emissions mt CO ₂ e	Biogenic CO ₂ emissions mt CO ₂	Lime kiln biogenic CO ₂ emissions mt CO ₂	Additional electricity for biomass gasification mt CO ₂ e	Increase in electricity mt CO ₂ e	Emission savings (capture - increase in biomass emissions) mt CO ₂ e	CCS adoption (% of emissions to balance combustion and process GHG emissions)	
Alabama	3,124,329	846,276	12,972,874	1,313,187	71,624	205,222	2,554,899	25%	5%
Arkansas	1,106,634	303,430	4,139,018	470,840	25,681	72,395	901,280	27%	3%
Florida	2,173,232	533,069	6,506,287	827,176	45,116	147,193	1,832,472	33%	10%
Georgia	3,525,442	795,111	14,740,456	1,233,792	67,294	244,346	3,041,971	27%	6%
Idaho	285,401	92,305	1,442,962	143,233	7,812	17,547	218,455	20%	1%
Kentucky	542,285	131,941	1,538,103	204,737	11,167	36,815	458,325	35%	2%
Louisiana	2,431,031	460,574	7,815,380	714,683	38,980	175,505	2,184,944	34%	6%
Maine	1,005,885	57,780	3,695,127	89,658	4,890	83,235	1,036,231	37%	3%
Michigan	1,310,455	101,413	2,257,862	89,658	8,583	106,348	1,323,973	61%	4%
Minnesota	413,432	85,931	2,123,890	133,341	7,273	29,239	364,013	24%	2%
Mississippi	859,861	287,264	4,777,094	445,755	24,312	52,134	649,043	18%	1%
North Carolina	1,650,806	295,098	5,587,131	457,911	24,976	120,590	1,501,272	34%	3%
Oklahoma	1,006,561	295,098	1,254,863	457,911	24,976	64,321	800,759	51%	12%
South Carolina	1,952,175	386,297	8,694,583	599,427	32,694	139,620	1,738,192	27%	7%
Tennessee	978,875	132,206	2,853,079	205,147	11,189	74,926	932,784	40%	2%
Texas	1,111,443	271,381	4,194,287	421,109	22,968	75,377	938,407	28%	5%
Virginia	2,173,788	355,653	4,869,338	551,876	30,101	161,426	2,009,661	46%	4%
Washington	1,153,006	297,840	5,107,792	462,166	25,208	76,892	957,265	25%	3%
Wisconsin	2,926,758	57,780	1,166,683	89,658	4,890	194,321	2,419,185	100%	6%
SUMS	29,731,398	5,786,448	95,736,806	8,911,265	489,733	2,077,453	25,863,131	33%	5%

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