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AVOIDED GREENHOUSE GAS EMISSIONS FROM US PULP AND PAPER INDUSTRY BIOMASS-DERIVED ELECTRICITY

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About this report:

The greenhouse gas (GHG) emission intensity characteristics of electricity generated by the US pulp and paper sector are presented in this report. The US pulp and paper sector generates 95% of its on-site electricity via combined heat and power (CHP). CHP systems, sometimes referred to as cogeneration units, generate both steam and electricity; therefore, it is necessary to allocate GHG emission impacts, as well as avoided emissions, from this sector via GHG allocation approaches. In this report, all major GHG allocation approaches are reviewed and applied to the US pulp and paper sector to generate allocation fractions for heat and electricity. Fenceline (only considering emissions generated or released by the facility) GHG emission intensities for the US pulp and paper sector, excluding consideration of avoided emissions, ranged from 82 to 316 g CO_2e/kWh, depending on the allocation approach used. Incorporating consideration of avoided life cycle GHG emissions from biomass utilization for energy generation within the US pulp and paper sector results in large negative emission intensities for industry-generated electricity. When incorporating avoided emissions and considering GHG allocation approaches to allocate avoided emissions to steam and electricity generation, life cycle GHG emission intensities from industry-generated electricity range from (709) to (2814) g CO_2e/kWh for electricity derived from spent liquor solids and range from (482) to (1812) g CO_2e/kWh for electricity derived from all other biomass sources[1]. The functions of the kraft recovery system that utilize black liquor, a by-product of the kraft pulping process, not only generate energy but recover pulping chemicals and manage black liquor solids and thus confer additional avoided GHG emissions when alternative use scenarios are considered compared to other biomass sources. Even when a portion of the electricity used in a pulp and paper mill is derived from supplemental fossil fuels, as is typical for the US pulp and paper sector, the large negative (i.e., avoided) emissions from utilizing biomass residuals more than offset the life cycle GHG emission amounts from use of fossil fuels, resulting in negative emissions for industry-generated electricity.

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.

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[1] Note that the use of parentheses in this report indicates negative emissions (i.e., avoided emissions).

AVOIDED GREENHOUSE GAS EMISSIONS FROM US PULP AND PAPER INDUSTRY BIOMASS-DERIVED ELECTRICITY

EXECUTIVE SUMMARY

Although the US pulp and paper sector is the largest contributor to biomass-derived electricity in the US, primarily through energy efficient combined heat and power systems, all previous life cycle studies on the greenhouse gas (GHG) emission characteristics of biomass-derived energy have either focused upon the exclusive generation of electricity or have focused upon energy generation without allocating GHG benefits and burdens between steam and electricity. The US pulp and paper sector generates 95% of its on-site electricity needs via combined heat and power (CHP). CHP systems, sometimes referred to as cogeneration units, generate both steam and electricity; therefore, it is necessary to allocate the GHG emission impacts, as well as avoided emissions, from this sector via GHG allocation approaches. In this report, all major GHG allocation approaches are reviewed and applied to the US pulp and paper sector to generate allocation fractions for heat and electricity. Fenceline (only considering emissions generated or released by the facility) GHG emission intensities for the US pulp and paper sector, excluding consideration of avoided emissions, ranged from 82 to 316 g CO_2e/kWh, depending on the allocation approach used. In a series of studies on the GHG benefits of biomass energy consumption in the US forest products sector, National Council for Air and Stream Improvement, Inc. (NCASI) provided information on the avoided life cycle GHG emissions from biomass utilization for energy generation in the sector (NCASI 2011; Gaudreault et al. 2012; NCASI 2013 (revised 2014); NCASI 2017). Incorporating avoided emissions and considering GHG allocation approaches to allocate avoided emissions to steam and electricity generation, life cycle GHG emission intensities from industry-generated electricity range from (709) to (2814) g CO_2e/kWh for electricity derived from spent liquor solids and range from (482) to (1812) g CO_2e/kWh for electricity derived from all other biomass sources. The functions of the kraft recovery system that utilize black liquor, a by-product of the kraft pulping process, not only generate energy but recover pulping chemicals and manage black liquor solids and thus confer additional avoided GHG emissions when alternative use scenarios are considered compared to other biomass sources. Even when a portion of the on-site electricity generation at a pulp and paper mill is derived from supplemental fossil fuels, as is typical for the US pulp and paper sector, the large negative (i.e., avoided) emissions from utilizing biomass residuals more than offset the life cycle GHG emission amounts from the use of fossil fuels, resulting in negative emissions for industry-generated electricity.

KEYWORDS

greenhouse gas emissions, avoided greenhouse gas emissions, pulp and paper, electricity generation, biomass

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AVOIDED GREENHOUSE GAS EMISSIONS FROM US PULP AND PAPER INDUSTRY BIOMASS-DERIVED ELECTRICITY

1.0 Introduction

In 2018, 4.181 trillion kWh of electricity was generated in the United. States[2]. Of this amount, 0.7068 trillion kWh of electricity, or 17% of total generation, was generated from renewable sources. Of the 17% of total generation from renewables, biomass-based electricity generation represented 61.83 billion kWh of electricity generation, or 2% of total generation (Figure 1). The US Environmental Protection Agency's (EPA) emission and generation resource integrated database (eGRID)[3] is a comprehensive source of data on electricity generation in the US. eGRID classifies electricity generation from hydro, biomass, wind, solar, and geothermal energy sources as renewable electricity generation.

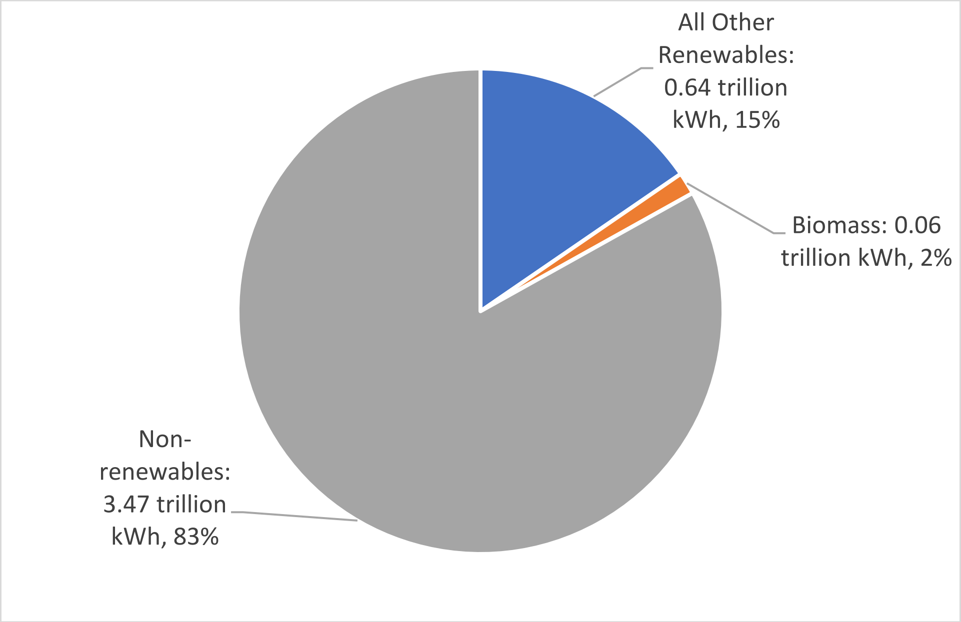

Figure 1. Electricity Derived from Renewables and Non-renewable Energy Sources in the US in 2018

In 2018, biomass-derived electricity represented 8.7% of total generation from renewable sources. Biomass-derived electricity from the US pulp and paper sector represented nearly half of the electricity generated nationally from biomass energy sources and was 30.79 billion kWh in 2018 (Figure 2)[4].

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[2] US Energy Information Administration (EIA) Electricity Overview. https://www.eia.gov/totalenergy/data/monthly/pdf/sec7_3.pdf

[3] US EPA Emission & Generation Resource Integrated Database (eGRID). https://www.epa.gov/egrid

[4] US EIA MECS. "Table 11.3 Electricity: Components of Onsite Generation, 2018." https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

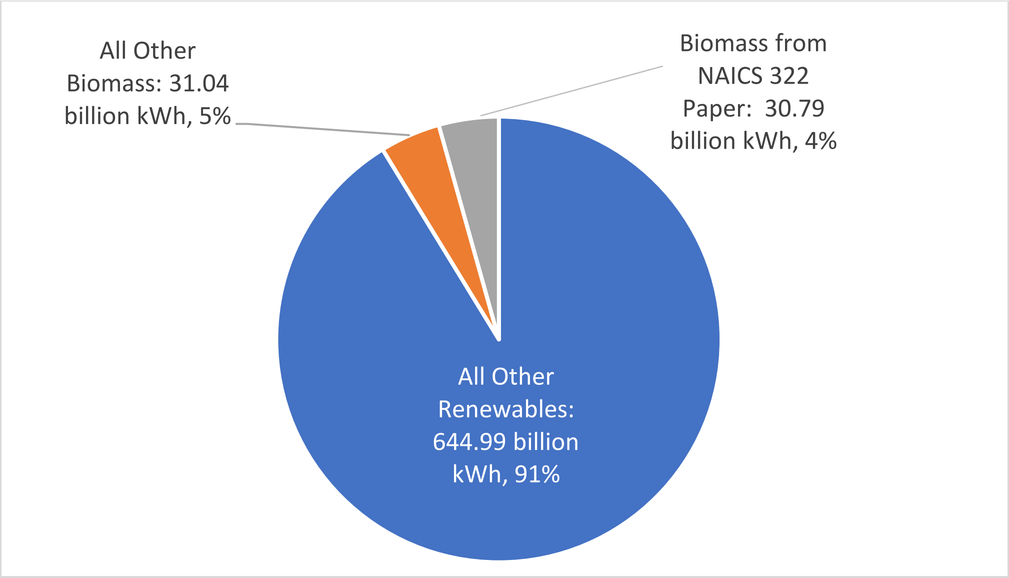

Figure 2. *Electricity Derived from Renewable Energy Sources in the US in 2018*

Although the US pulp and paper sector is the largest contributor to biomass-derived electricity in the US, primarily through energy efficient CHP systems, all previous life cycle studies on the greenhouse gas (GHG) emission characteristics of biomass-derived energy have either focused upon the exclusive generation of electricity or have focused upon energy generation without allocating GHG benefits and burdens between steam and electricity (Reviews of the state of the exclusive generation of bio-based electricity can be found in EPRI (2013); NCASI (2014); and NREL (2021).) The pulp and paper sector generates steam *and* electricity, predominately through efficient CHP systems, and therefore, GHG burdens and avoided emissions must be allocated between the steam and electricity co-products. The goal of this white paper is to quantify life cycle GHG emissions from industry-generated electricity, including avoided emissions, from the use of biomass residual fuels. The GHG characteristics of pulp and paper mill electricity generation when on-site use of fossil fuels supplements a portion of the heat and power needs at the mill, which is a typical scenario at US pulp and paper facilities, is also estimated.

2.0 Summary

The US pulp and paper sector generated 95% of its total on-site generation of electricity via CHP in 2018. Because CHP systems generate steam and electricity, it is necessary to allocate the GHG emission impacts, as well as avoided emissions, via GHG allocation approaches. An overview of the most prominent allocation approaches applied to the pulp and paper sector is provided in Appendix C. Fenceline GHG emission intensities (i.e., only considering emissions generated or released by the facility) for the US pulp and paper sector, excluding consideration of avoided emissions, ranged from 82 to316 g CO_2e/kWh, depending on the allocation approach used. In a series of studies on the GHG benefits of biomass-derived energy consumption in the US forest products industry, National Council for Air and Stream Improvement, Inc. (NCASI) provided information on the avoided life cycle GHG emissions from biomass utilization for energy generation in the sector (NCASI 2011; Gaudreault et al. 2012; NCASI 2013 (revised 2014); NCASI 2017). Incorporating avoided emissions and using a spectrum of major GHG allocation approaches to allocate avoided emissions to steam and electricity generation, life cycle GHG emission intensities from industry-generated electricity range from (709) to (2814) g CO_2e/kWh for electricity derived from spent liquor solids and from (482) to (1812) g CO_2e/kWh for electricity derived from all other biomass sources[5], depending on the allocation approach used. Even when a portion of the electricity used in a pulp and paper mill is derived from supplemental fossil fuels, as is typical for the US pulp and paper sector, negative emissions for industry-generated electricity are calculated because the large negative (i.e., avoided) emissions from utilizing biomass residuals more than offset the life cycle GHG emission amounts from using fossil fuels.

3.0 Previous Studies

Life cycle GHG emission intensity for stand-alone biomass-derived electricity generation, excluding consideration of avoided emissions, ranges from 15 to 130 g CO_2e/kWh from previous work and from several meta-analyses (compilations of life cycle assessment studies).

Table 1. *Life Cycle Emission Factors for Electricity Generation from Previous Studies or Meta-analyses*

Fuel	Emission Intensity (g CO_2e/kWh)	Emission Intensity Type	Source
Biomass	42	Median	IPCC (2011)
Mill Residue	15	Median, harmonized	EPRI (2013)
Biomass	8.5 to 130	Range	Turconi et al. (2013)
Biomass	52	Median, harmonized	NREL (2021)
Forest Biomass	49	Average	Xu et al. (2021)
Forest Residue	72	Point calculation	Cuellar and Herzog (2015)
Considering Avoided Emissions			
Biomass	(410)	Point calculation	Spath and Mann (2004)
Biomass	0 to (900)	Point calculations	IPCC (2011)
Mill Residue	(1000)	Point calculation	EPRI (2013)
Biomass	0 to (1000)	Point calculations	NREL (2021)
Considering Avoided Emissions and Engineered Carbon Mitigation (Carbon Capture and Storage)			
Biomass	(667) to (1368)	Point calculations	Spath and Mann (2004)
Biomass	(600) to (1368)	Point calculations	IPCC (2011)
Biomass	(600) to (1368)	Point calculations	NREL (2021)
Forest Residue	(1818)	Point calculation	Cuellar and Herzog (2015)

When avoided emissions are considered, life cycle GHG emission intensities for stand-alone biomass to electricity generation become negative, ranging from (410) to (1000) g CO_2e/kWh. Additional GHG savings can be achieved with the employment of engineered GHG mitigation strategies such as bioenergy carbon capture and storage (BECCS). It is important to note that BECCS installations at pulp

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[5] Biomass refers primarily to woody residuals from manufacturing but also wastewater treatment plant residuals, paper recycling residuals, residuals from forest harvesting, and other miscellaneous biomass fuels used by the US pulp and paper sector.

and paper mills are currently not widespread and only exist at the demonstration or pilot scale. A review of the state of carbon capture in the pulp and paper sector is provided in the NCASI white paper “Toward a Net Zero Future for the Forest Products Industry” (2023b). Considering BECCS, life cycle GHG emission intensities for biomass to electricity generation of (600) to (1818) g CO_2e/kWh can be achieved. A summary of study results is provided in Table 1. It is important to note that previous studies focused on stand-alone biomass electricity generation plants while this white paper provides information on the life cycle GHG emission characteristics of biomass-derived electricity from US pulp and paper facilities.

Figure 3 shows meta-analyses life cycle GHG emission estimates from bio-based electricity generation from the “Bioenergy” chapter of the Intergovernmental Panel on Climate Change (IPCC) special report on renewable energy sources and climate change mitigation (IPCC 2011). Median life cycle emissions were 42 g CO_2e/kWh. When avoided emissions are considered, emissions of up to (900) g CO_2e/kWh are calculated, and when engineered GHG mitigation approaches such as BECCS are considered in addition to avoided emissions, emissions of (600) to (1368) g CO_2e/kWh are calculated. Again, carbon capture installations at pulp and paper mills are currently not widespread and only exist at the demonstration or pilot scale.

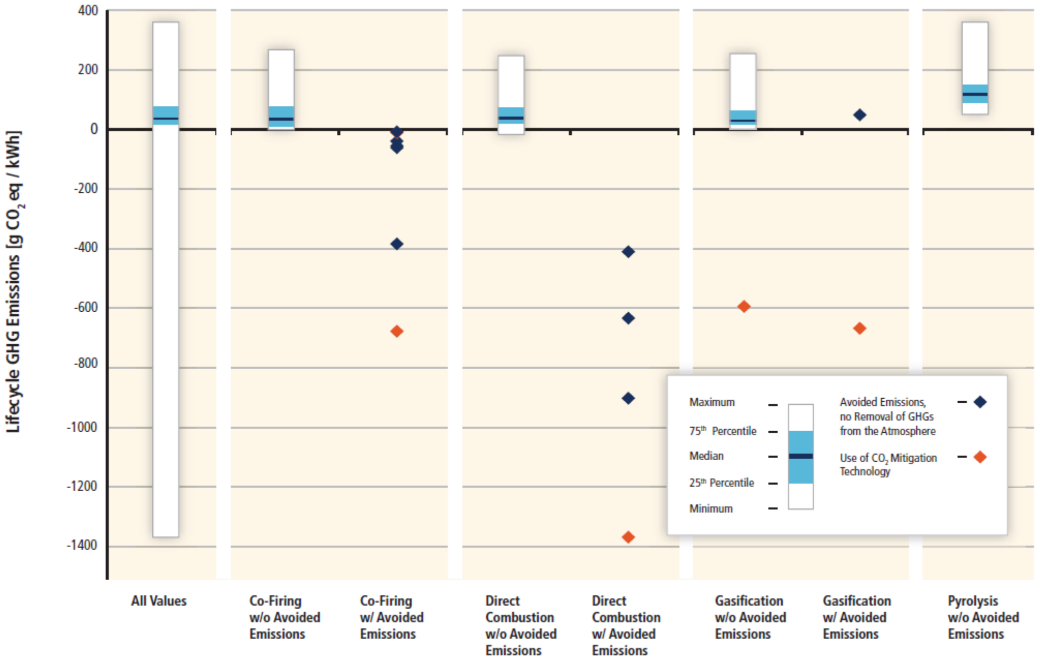

Figure 3. *Life Cycle GHG Emission Estimates from Bio-Based Electricity Generation (IPCC 2011)*

Figure 4 shows harmonized meta-analyses of life cycle GHG emission estimates from all major energy sources used for electricity generation (NREL 2021). NREL’s life cycle harmonization project is a meta-analytical procedure to assess and reduce the variability of life cycle assessment results (Heath and Mann 2012). Median, harmonized life cycle emissions for biomass-derived electricity generation were 52 g CO_2e/kWh. When avoided emissions are considered, emissions of up to (1000) g CO_2e/kWh are calculated, and when engineered GHG mitigation approaches such as BECCS are considered in addition to avoided emissions, emissions of (600) to (1368) g CO_2e/kWh are calculated.

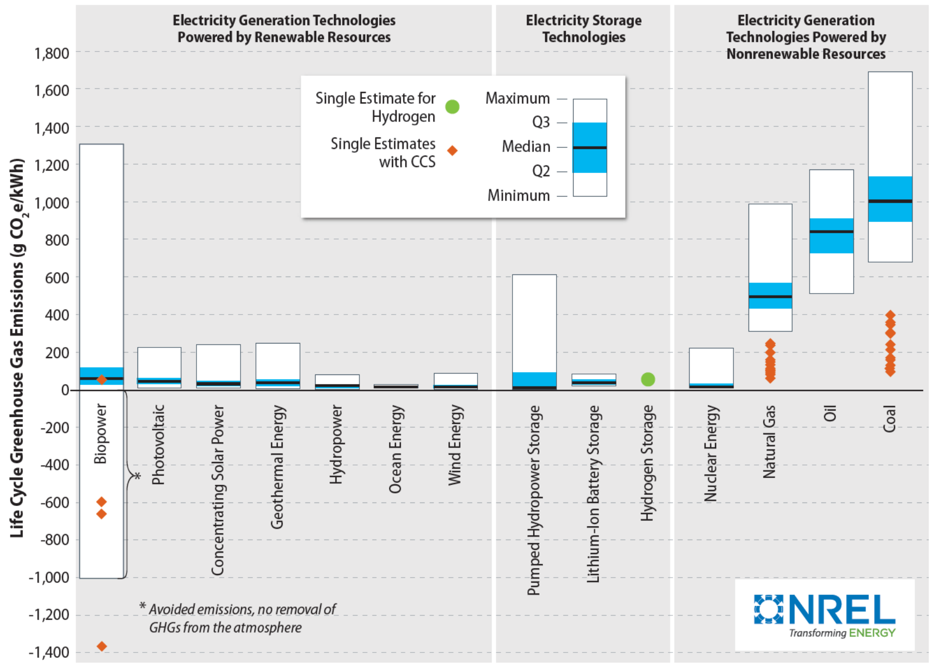

Figure 4. *Life Cycle GHG Emission Estimates from Electricity Generation and Storage Technologies and Some Technologies Integrated with Carbon Capture and Storage (NREL 2021)*

Figure 5 and Figure 6 show life cycle GHG emission estimates for different types of biomass used for electricity generation (EPRI 2013). Median, harmonized life cycle emissions for electricity generation from mill biomass residues were 15 g CO_2e/kWh. When avoided emissions are considered, negative emissions of (1000) g CO_2e/kWh were calculated (point emission calculation).

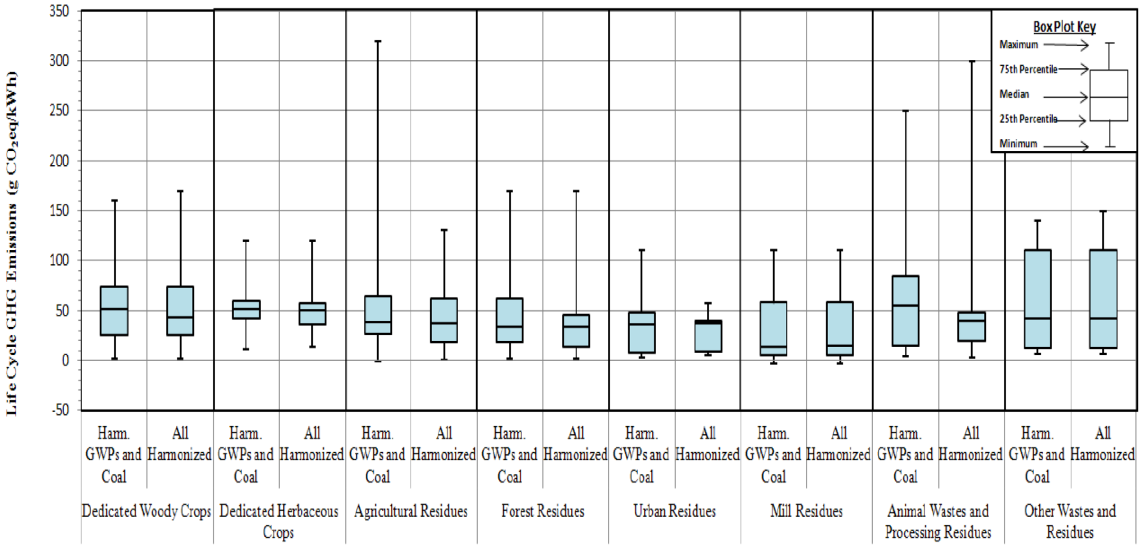

Figure 5. *Distribution of Life Cycle GHG Emission Estimates from Electricity Generation by Feedstock Categories (EPRI 2013)*

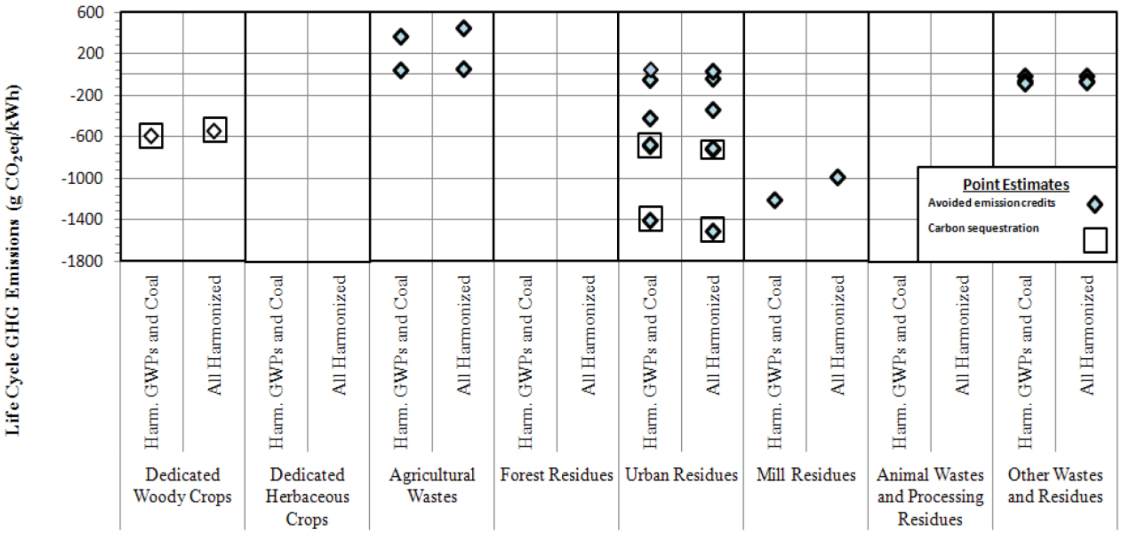

Figure 6. *Point Estimates of Life Cycle GHG Emission Estimates from Electricity Generation by Feedstock Categories (EPRI 2013)*

Xu et al. studied the regionality of life cycle emissions within the US for forest biomass-derived electricity (2021), shown in Figure 7. Forest biomass-derived electricity has 86% to 93% lower life cycle GHG emissions than average grid electricity in the US (Xu et al. 2021). The average of life cycle emissions of forest biomass-derived electricity was 49 g CO_2e/kWh from several US states (Xu et al. 2021).

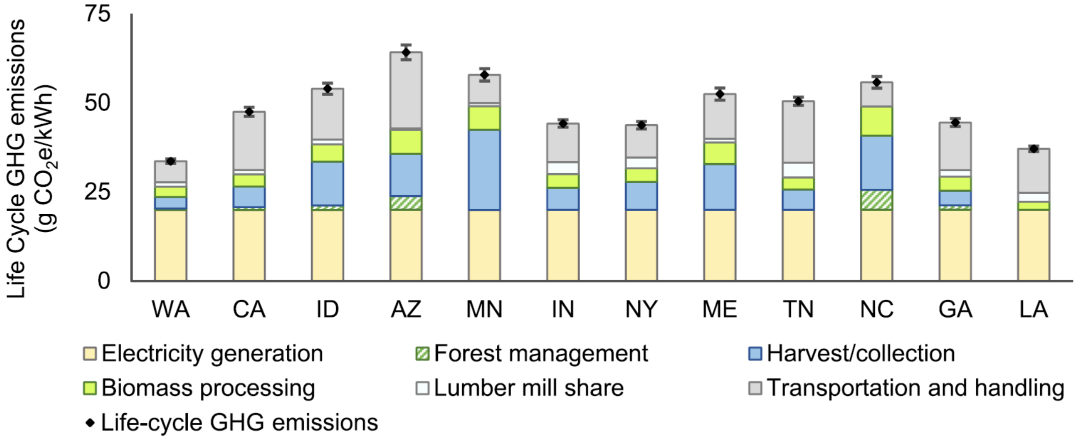

Figure 7. *Life Cycle GHG Emission Estimates for Woody Biomass by US State and by Life Cycle Stage (Xu et al. 2021)*

4.0 Biomass Fuel Types used for Electricity Generation with the US Pulp and Paper Sector

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 CO_2 emissions for the US forest products sector were 137 million mt CO_2e (115 million mt CO_2e from the pulp and paper sector and 22 million mt CO_2e 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.

4.1 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 then 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 into sewers can have chemical recovery efficiencies approaching 99% (NCASI 2023a).

Due to the importance of the kraft process to the pulp and paper sector[6], NCASI undertook a life cycle-based assessment of the benefits of using black liquor solids (NCASI 2011; Gaudreault et al. 2012). 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 CO_2e 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 mt CO_2e per year. These avoided emissions are greater than the total of Scope 1 and 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 CHP cogeneration systems, 80% to 90% of the GHG benefits are retained.

Combustion of spent liquor solids for energy generation represented 919 trillion Btu of energy in 2018 for the US pulp and paper sector, or approximately 75% of all biomass fuels utilized by the sector[7].

4.2 Manufacturing Biomass Residuals

The use of manufacturing and forest biomass residuals in power boilers is a long-established practice within the forest products industry (both the pulp and paper sector and the wood products sector). Combustion of biomass residuals other than spent liquor solids for energy generation represented

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[6] 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.

[7] US EIA MECS Survey Data. https://www.eia.gov/consumption/manufacturing/data/2018/

304 trillion Btu of energy in 2018 for the US pulp and paper sector[8]. For the US wood products sector, combustion of biomass residuals represented 233 trillion Btu of energy in 2018. US forest products industry mill manufacturing residuals represent most biomass residuals other than spent liquor solids (Figure 8). Smaller amounts of logging biomass residuals, residuals from wastewater treatment plant operations, paper recycling residuals, and other miscellaneous biomass residuals are utilized by the US forest products industry for energy generation or solid residual minimization. The US pulp and paper sector's contribution from biomass residuals other than spent liquor solids for energy generation is similar to the US forest products industry (Figure 9).

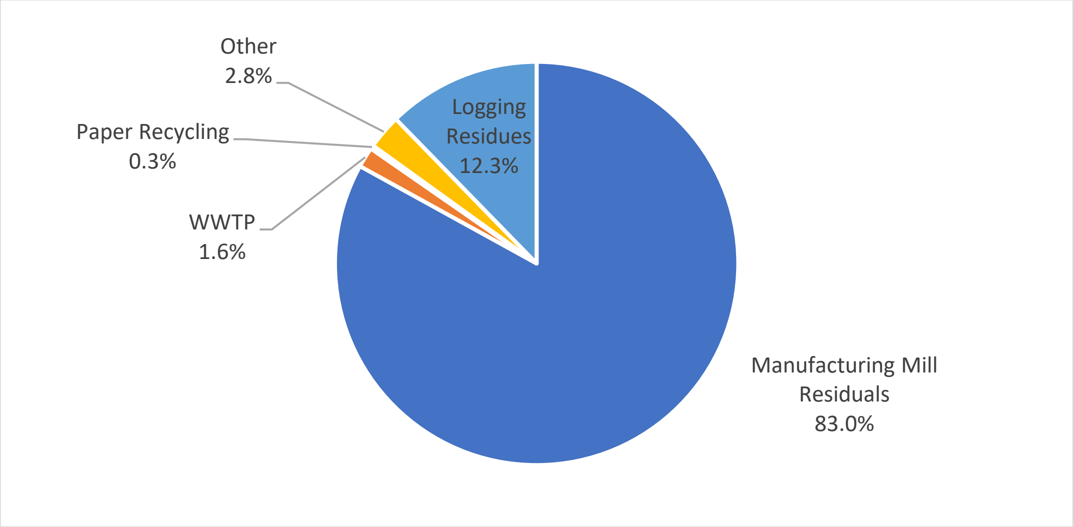

Figure 8. *Energy Fractions for US Forest Products Industry's (Both Pulp and Paper and Wood Products Sectors) Biomass Residuals Other Than Spent Liquor Solids*

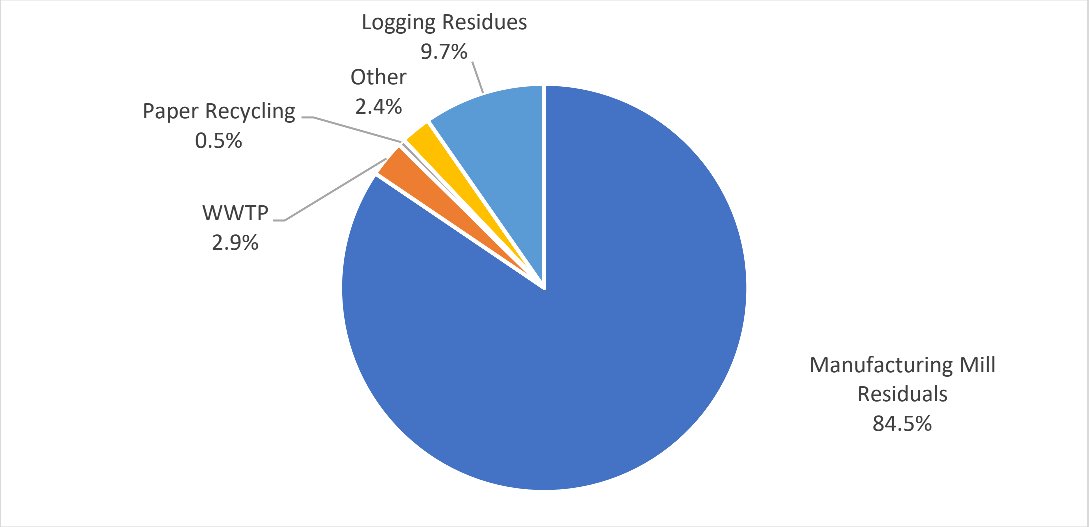

Figure 9. *Energy Fractions for the US Pulp and Paper Sector's Biomass Residuals Other Than Spent Liquor Solids*

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[8] US EIA MECS Survey Data. https://www.eia.gov/consumption/manufacturing/data/2018/

5.0 Combined Heat and Power

The forest products industry is a leader in the use of CHP, also known as cogeneration, 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) CHP (US EPA 2017; NREL 2017; DGA et al. 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 2).

Table 2. *US Forest Products Industry Installed CHP Capacity*[9]

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

The US forest products industry produced 32% of all the CHP power generated by manufacturing industries in 2018[10]. Over 40 billion kWh of electricity was generated through CHP by the US forest products industry in 2018, representing 95% of all on-site electricity generated by the sector (see Table 3). Pulp and paper and wood product facilities predominantly use biomass-based CHP to generate steam and electricity with very low GHG emissions. The US pulp and paper sector avoids over 12 million mt CO_2e annually by using CHP compared to the separate generation of steam and electricity (Appendix A). The forest products sector sold 6449 million kWh of energy in 2018, which helps contribute to greening 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, i.e., electricity can still be generated and utilized at a mill even during grid power disruptions or outages. Table 3 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 and electricity sales within the wood products sector represented 59% of total sector electricity generation.

Total CHP efficiencies (energy content of steam and electricity divided by energy content of fuels) of 65-75% are common for CHP (including forest product) systems (EPA 2017; NREL 2017; DGA et al. 2015).

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[9] U.S. Department of Energy Combined Heat and Power and Microgrid Installation Databases. CHP Data Download. https://doe.icfwebservices.com/downloads/chp

[10] US EIA MECS: "Table 11.3 Electricity: Components of Onsite Generation, 2018." https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

Table 3. *The US Forest Products Industry Electricity Generation Profile*

Sector	Cogenerated Electricity[a] (million kWh)	Total On-site Electricity Generation[b] (million kWh)	Percentage of On-site Electricity that Is Cogenerated	Sales[b] (million kWh)
Pulp and Paper	38,663	40,518	95%	5372
Wood Products	1735	1840	94%	1077
Forest Products (Total)	40,398	42,358	95%	6449

[a] US EIA MECS: "Table 11.3 Electricity: Components of Onsite Generation, 2018."
https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf
[b] US EIA MECS: "Table 11.1 Electricity: Components of Net Demand, 2018."
https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_1.pdf

A diagram of a typical steam and power balance at a medium-sized kraft mill is provided in Figure 10. Typically, high-pressure steam is produced from a kraft recovery boiler and one or more power boilers. Fuels used in mill power boilers may be biomass fuels or fossil fuels (predominantly natural gas, but small amounts of coal and residual fuel oil may also be used).

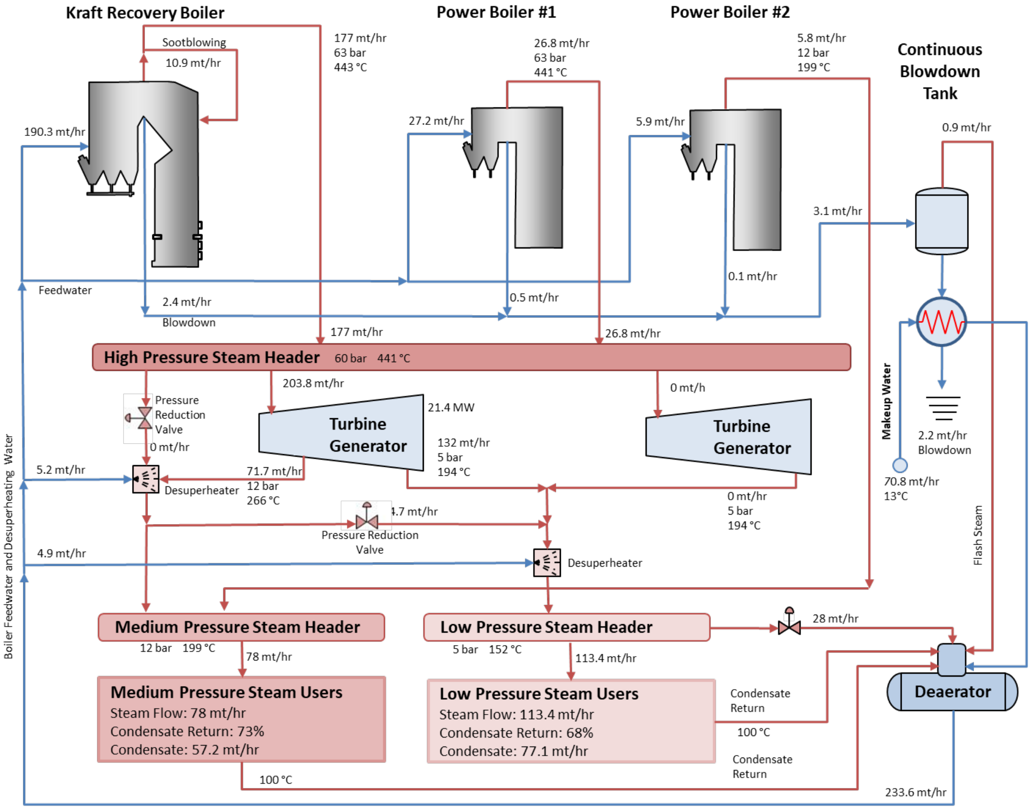

Figure 10. *Typical Steam and Power Balance at a Kraft Mill (Reproduced from AGRA Simons 1998)*

A simplified block diagram of a chemical pulp mill CHP system is provided in Figure 11. Mill CHP systems typically have multiple biomass or fossil fuels supplying energy to the system. The nature of CHP systems is that they simultaneously produce multiple products (medium- and low-pressure steam to supply mill needs and electricity for use or sale).

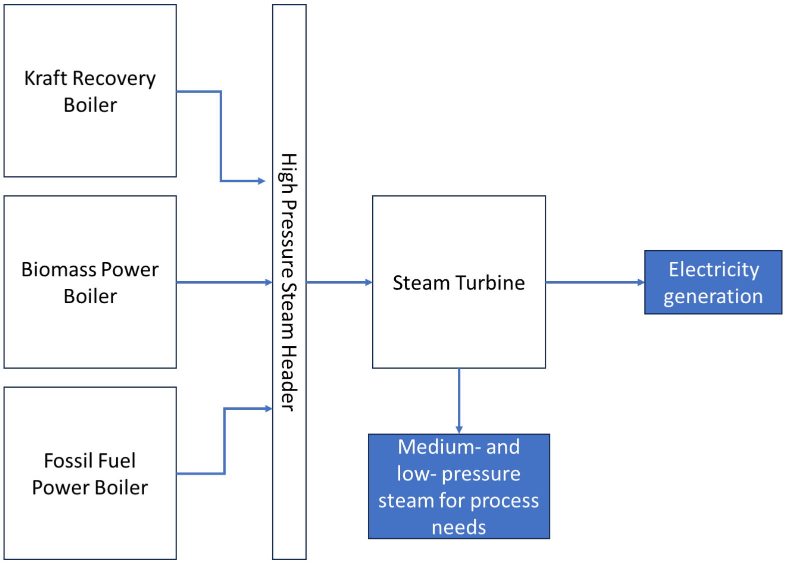

Figure 11. *Simplified Block Diagram of a Chemical Pulp Mill CHP System (steam and electricity co-products are highlighted in blue)*

In detailed cradle to final energy use life cycle studies on the GHG and fossil fuel reduction benefits of using biomass residuals for energy production (NCASI 2011; Gaudreault et al. 2012; NCASI 2014; NCASI 2017), life cycle GHG emissions were determined for biomass residual fuels used in the US forest products sector. The Life Cycle Assessment (LCA) methodology and boundary conditions used in the NCASI LCAs are provided in Appendix B. For each type of residual, the NCASI studies compared a base case of no beneficial use of residuals (including their alternative fates) with 100% use for energy generation. A summary of the differential GHG impact indicators is provided in Table 4.

Table 4. *Difference in Total Life Cycle GHG Emissions Over 100 Years*

Biomass Residual Type	Differential GHG Impact, Dynamic Forcing (kg CO_2e/GJ)
Woody Mill Residuals[a]	-116
WWTP Residuals[a]	-295
Paper Recycling Residuals[a]	-112
Spent Liquor (Including Black Liquor)[B]	-184
Forest Harvesting Residuals[c]	-75.7

[a] NCASI 2014
[b] NCASI 2011; Gaudreault et al. 2012
[c] NCASI 2017

The differential GHG impact indicator is defined as:

> Differential GHG Impact (kg CO_2E/GJ) = [Total GHG impact caused by GHG releases, including biogenic CO_2 emissions and removals, for energy production using residuals] – [Total GHG impact of GHG releases, including biogenic CO_2 emissions and removals, for energy production using fossil fuels, including alternative fate of residuals] (NCASI 2014).

A summary of GHG mitigation benefits of energy generation from biomass residuals in the US forest products sector is provided in Table 5. Even in the LCA scenarios where it was assumed the no GHG benefit was derived from the displacement of fossil fuels, negative GHG impact indicators were calculated for biomass fuel sources; woody mill residuals: -8.5 kg CO_2e/GJ; WWTP residuals: -190 kg CO_2e/GJ; paper recycling residuals[11]: -132 kg CO_2e/GJ; and spent liquor (including black liquor) solids[12]: -78.2 kg CO_2e/GJ (NCASI 2011; Gaudreault et al. 2012; NCASI 2014).

Table 5. *Life Cycle GHG Mitigation Benefits for Biomass Residuals Energy Systems in the US Forest Products Sector*

Reference	Biomass Type	Fossil Fuels Offset	Type Of Facility in which the Biofuel Is Used	Alternative Fate Considered	GHG Mitigation Compared to a Comparable Fossil Fuel-Based System (%)	Break-even Time (years)[a]
Gaudreault et al. (2012) and NCASI (2011)	Black liquor	Heat (coal and natural gas) or CHP (coal and natural gas for heat and US electricity grid for electricity)	US pulp and paper mills	Biogenic carbon released as CO_2	69–92	0
NCASI (2014)	Woody mill residuals		US forest products facilities	Landfill or incineration	98.7	1.2
NCASI (2014)	WWTP[b] residuals		US pulp and paper mills	Landfill or incineration	98.7	0
NCASI (2014)	Paper recycling residuals		US pulp and paper mills	Landfill or incineration	86.4	0
NCASI (2017)	Forest residuals		US forest products facilities	Decay or burned on-site	92.5	0

[a] Based on dynamic radiative forcing.
[b] Wastewater treatment plant.

6.0 Allocation of Life Cycle GHG Emissions to Steam and Electricity

In detailed cradle to final energy use life cycle studies on the GHG and fossil fuel reduction benefits of using biomass residuals for energy production (NCASI 2011; Gaudreault et al. 2012; NCASI 2014; NCASI

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[11] Consideration of the fiber fraction only.

[12] Only considering the differential GHG impact from the alternative production of pulping chemicals and assuming the most conservative result for the alternative management of black liquor (all biogenic carbon returns to the atmosphere as CO_2 compared to a portion being released to the atmosphere as methane). More realistic alternative fate analyses would generate a more highly negative differential GHG impact factor because methane would be generated in those scenarios.

2017), the functional unit was the production of 1 GJ of energy. Given that over 95% of the on-site electricity in the US pulp and paper sector is generated from CHP systems, allocation approaches to allocate both GHG burdens and benefits are required to quantify the GHG characteristics of industry-generated biomass-derived electricity. Appendix B provides a detailed overview of the most common GHG allocation approaches applied to the US pulp and paper sector. Depending on the approach, different fractional allocation amounts are attributed to heat or electricity (Table 6).

Table 6. *US Pulp and Paper Sector GHG Allocation Fractions for CHP Systems by Method*

Allocation Method	Fraction Allocated to Electricity f_E	Fraction Allocated to Heat f_Q
Energy Content	0.13	0.87
Incremental Fuel Consumption (Electricity)	0.21	0.79
Work Potential Method	0.22	0.78
Incremental Fuel Consumption (Steam)	0.24	0.76
Simplified Efficiency Method	0.26	0.74
Economic Value Method	0.50	0.50

Avoided GHG emissions can be determined by the use of the differential GHG impact indicators in Table 4 and current energy consumption information for biomass residuals for the US pulp and paper sector (Appendix A). Table 7 shows the calculated avoided emissions on an absolute basis and life cycle GHG emission intensities allocated to electricity production for the US pulp and paper sector.

Table 7. *Life Cycle GHG Emission Characteristics of Biomass-derived Electricity Considering Avoided Emissions for the US Pulp and Paper Sector*

Biomass Residual	Avoided GHG Emissions (million mt CO_2e)	Life Cycle GHG Emission Intensities Allocated to Electricity Production	
		Low (kg CO_2e/MWh)	High (kg CO_2e/MWh)
Spent Pulping Liquor	119	(709)	(2814)
All Other Biomass Residuals	25	(482)	(1812)

Electricity efficiencies (the ratio of power output to fuel input on a higher heating value energy basis) of systems designed for the exclusive generation of electricity are higher than in CHP systems. New ultra-supercritical coal-based electricity generation plants have electricity efficiencies of 40% (heat rate of 8368 Btu/kWh), and new natural gas combined cycle multi-shaft electricity generation plants have electricity efficiencies of 54% (heat rate of 6370 Btu/kWh) (US EIA 2023). In a meta-analysis of life cycle GHG emissions of coal-fired electricity generation, electricity efficiencies ranged from 27% to 49%, and a collective harmonized arithmetic weighted mean thermal efficiency was 33% (Whitaker et al. 2012). In a meta-analysis of life cycle GHG emissions of natural gas fired electricity generation, electricity efficiencies ranged from 43% to 50% (O'Donoughue et al. 2014). Because of the higher electricity efficiencies for stand-alone plants, allocated emissions from CHP systems can be greater than from electricity-only plants (column 2 of Table 8).

Table 8. *Life Cycle GHG Emission Characteristics of Fossil Fuel Derived Electricity*

Fossil Fuel Used in the Pulp and Paper Sector	Total Life Cycle Emissions for Electricity Production (kg CO_2e/MWh)[a]	Life Cycle GHG Emission Intensities Allocated to Electricity Production (kg CO_2e/MWh)	
		Low	High
Natural Gas	486	296	1137
Coal	1001	411	1581

[a] NREL 2021

In a detailed study of combined heat and power generation and the avoided emissions from the energy efficiency improvement of CHP systems compared to the separate generation of steam and electricity (Appendix A), the fuel and energy usage and energy generation characteristics of 177 US pulp and paper mills were aggregated and assessed to generate GHG information on average and total CHP generation in the US pulp and paper sector. In 2018, 24% of steam and power from US pulp and paper sector CHP systems were derived from fossil fuels (19% natural gas, 3% coal, 2% other fossil fuels) (Appendix A and Figure 12).

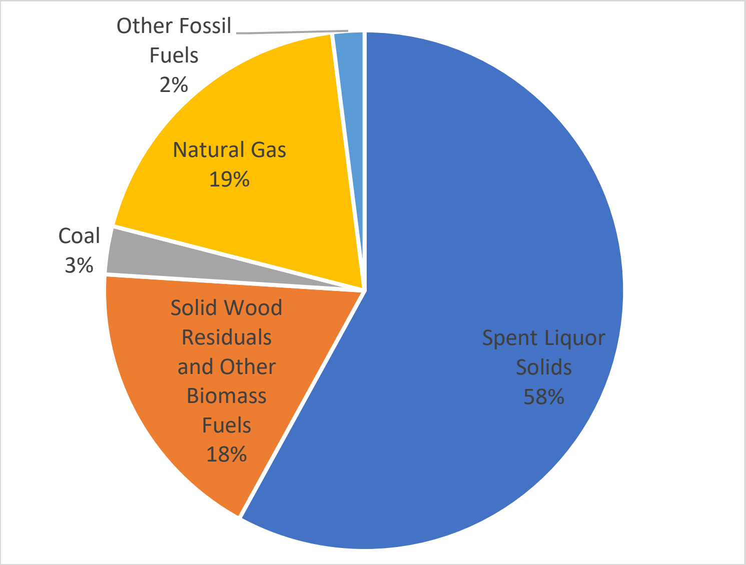

Figure 12. *Fuels Used in US Pulp and Paper Sector Cogeneration Systems in 2018*

The emission factor for a CHP system using multiple fuels can be calculated as:

$$EF_{\text{CHP}} = \sum_{i=1}^{i=n} \frac{\left(F_{\text{fuel}_i} \cdot \eta_{\text{eff}_i}\right) \cdot EF_i}{\sum_{i=1}^{i=n}\left(F_{\text{fuel}_i} \cdot \eta_{\text{eff}_i}\right)}$$

Where:

F_{fuel}:	fuel fraction on a higher heating value energy basis
EF:	emission intensities for electricity generation for biomass fuels (Table 7) or fossil fuels (Table 8)
η_{eff}:	boiler thermal efficiency by fuel (Appendix A, Table)

Emission intensities attributed to electricity generation from biomass fuels (Table 7), fossil fuels (Table 8), and typical boiler thermal efficiencies by fuel (Appendix A, Table), can be used in the above equation to calculate composite emission intensities from mill-produced electricity. Under a typical scenario where 24% of the fuel was supplied from either natural gas or coal, industry derived electricity is still significantly negative from a GHG perspective when avoided emissions from the utilization of biomass fuels are considered (Table 9).

Table 9. *GHG Emission Characteristics of US Pulp and Paper Sector Produced Electricity*

Mill Fossil Fuel Fraction for Energy Generation[a]	Life Cycle GHG Emission Intensities Allocated to Electricity Production	
	Low (kg CO_2e/MWh)	High (kg CO_2e/MWh)
24% Coal	(346)	(1368)
24% Natural Gas	(388)	(1534)
19% Natural Gas, 5% Coal	(379)	(1499)

[a] 58% of energy is derived from black liquor, and 18% is derived from other biomass fuels.

7.0 Conclusions

This white paper provides information regarding the life cycle GHG characteristics of biomass-derived electricity from the US pulp and paper sector. When avoided emissions are considered, life cycle GHG emission intensities for industry-generated electricity derived from spent liquor solids and all other major biomass types utilized by the sector are highly negative. Even when a portion of the on-site electricity generation at a pulp and paper mill is derived from supplemental fossil fuels, as is typical for the US pulp and paper sector, the large negative (i.e., avoided) emissions from utilizing biomass residuals more than offset the life cycle GHG emission amounts from the use of fossil fuels, resulting in negative emissions for industry-generated electricity.

References

AGRA Simons and Pulp and Paper Technical Association of Canada. 1998. *A Guide to Energy Savings Opportunities in the Kraft Pulp Industry*. AGRA Simons Limited: Vancouver, BC; Pulp and Paper Technical Association of Canada: Brossard, QC.

Cuellar, Amanda D., and Howard Herzog. 2015. “A Path Forward for Low Carbon Power from Biomass.” *Energies* 8, no. 3: 1701–1715. https://doi.org/10.3390/en8031701.

David Gardiner and Associates (DGA), Institute for Industrial Productivity, and Wooley Energy & Environment. 2015. Combined Heat and Power (CHP) as a Compliance Option Under the Clean Power Plan: A Template and Policy Options for State Regulators. https://chpalliance.org/wp-content/uploads/2016/05/CHP-Pathway_Full-Report_Final.pdf.

US EIA (Energy Information Administration). March 2023. Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2023. Washington, D.C. https://www.eia.gov/outlooks/aeo/assumptions/pdf/elec_cost_perf.pdf.

US EPA (Environmental Protect Agency). 2017. Catalog of CHP Technologies. https://19january2021snapshot.epa.gov/sites/static/files/2015-07/documents/catalog_of_chp_technologies.pdf.

EPRI (Electric Power Research Institute). 2013. “Literature Review and Sensitivity Analysis of Biopower Life-Cycle Assessments and Greenhouse Gas Emission.” Palo Alto, CA. https://www.epri.com/research/products/1026852.

Gaudreault, Caroline, Barry Malmberg, Brad Upton, and Reid Miner. 2012. “Life Cycle Greenhouse Gases and Non-Renewable Energy Benefits of Kraft Black Liquor Recovery.” *Biomass and Bioenergy* 46:683–692. https://doi.org/10.1016/j.biombioe.2012.06.027.

Heath, Garvin A., and Margaret K. Mann. 2012. “Background and Reflections on the Life Cycle Assessment Harmonization Project.” *Journal of Industrial Ecology* 16, no. S1:S8–S11. https://doi.org/10.1111/j.1530-9290.2012.00478.x.

Chum, Helena, Andre Faajj, José Moreira, Göran Berndes, Parveen Dhamija, Hongmin Dong, Benoît Gabrielle, Alison Goss Eng, Wolfgang Lucht, Maxwell Mapako, Omar Masera Cerutti, Terry McIntyre, Tomoaki Minowa, and Kim Pingoud. 2011. “Bioenergy.” In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*: 209–332. Cambridge, UK and New York, US: Cambridge University Press. https://archive.ipcc.ch/pdf/special-reports/srren/Chapter%202%20Bioenergy.pdf.

NCASI (National Council for Air and Stream Improvement, Inc). April 2011. Greenhouse Gas and Non-Renewable Energy Benefits of Black Liquors Recovery. Technical Bulletin No. 984. Research Triangle Park, N.C.

———. October 2013 (revised August 2014). Greenhouse gas and fossil fuel reduction benefits of using biomass manufacturing residuals for energy production in forest products facilities. Technical Bulletin No. 1016. Research Triangle Park, N.C.

———. 2017. Greenhouse Gas Aspects of Using Forest Residuals for Energy Production in Forest Products Facilities. Technical Bulletin No. 1042. Research Triangle Park, N.C.

———. November 20, 2023a. Liquor Cycle Sodium Make-up Requirements at Kraft Pulp Mills. Technical Memorandum. Research Triangle Park, N.C.

———. 2023b. Toward a Net Zero Future for the Fores Products Industry. White Paper WP-23-04. Research Triangle Park, N.C.

NREL (National Renewable Energy Laboratory). 2017. Combined Heat and Power Evaluation Protocol. The Uniform Methods Project: Methods for Determining Energy Efficiency Savings for Specific Measures. NREL/SR-7A40-68579.

———. 2021. Life Cycle Greenhouse Gas Emissions from Electricity Generation: Update. NREL/FS-6A50-80580.

O'Donoughue, Patrick R., Garvin A. Heath, Stacey L. Dolan, and Martin Vorum. 2014. "Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas: Systematic Review and Harmonization." *Journal of Industrial Ecology* 18, no. 1: 125–144. https://doi.org/10.1111/jiec.12084.

Spath, Pamela L., and Margaret K. Mann. 2004. Biomass Power and Conventional Fossil Systems with and without CO_2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics. NREL/TP-510-32575. National Renewable Energy Laboratory, Golden, CO, USA.

Tran, Honghi, and Esa K. Vakkilainen. 2008. "The Kraft Chemical Recovery Process." Technical Association of the Pulp and Paper Industry. https://www.tappi.org/content/events/08kros/manuscripts/1-1.pdf

Turconi, Roberto, Alessio Boldrin, and Thomas Astrup. 2013. "Life Cycle Assessment (LCA) of Electricity Generation Technologies: Overview, Comparability and Limitations." *Renewable and Sustainable Energy Reviews* 28: 555–565. https://doi.org/10.1016/j.rser.2013.08.013.

Whitaker, Michael, Garvin A. Heath, Patrick O'Donoughue, and Martin Vorum. 2012. "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation: Systematic Review and Harmonization." Journal of Industrial Ecology 16(S1): S53–S72. https://doi.org/10.1111/j.1530-9290.2012.00465.x

Xu, Hui, Gregory Latta, Uisung Lee, Jan Lewandrowski, and Michael Wang. 2021. "Regionalized Life Cycle Greenhouse Gas Emissions Of Forest Biomass Use For Electricity Generation in the United States." *Environmental Science & Technology* 55, no. 21:14806–14816.

Appendix A: Avoided GHG Emissions from the Use of CHP in the US Pulp and Paper Industry

CHP is the sequential or simultaneous generation of useful thermal and electrical energy in a single integrated system. CHP is more energy efficient at generating steam and electricity than the separate generation of steam and electricity and can therefore result in fuel savings and GHG emission reductions.

One method of evaluating the efficiency of CHP systems within the pulp and paper industry is to compare emissions from CHP operation to emissions from the separate generation of equivalent amounts of steam for process use and electrical power. Avoided GHG emissions in 2018 due to the use of CHP for the US pulp and paper industry were 12.2 million mt CO_2e (Table A1). To put these avoided emissions in context, combined direct and indirect GHG emissions from the US pulp and paper industry were 53.0 million mt CO_2e in 2018 (Appendix A). Use of CHP technology in the US pulp and paper industry reduced GHG emissions by 34% compared to what they would have been if those mills had generated steam in stand-alone generation units and purchased all required electricity from the power grid (34.9 million mt CO_2e compared to 23.6 million mt CO_2e from CHP operation). In addition to the energy efficiency savings from the utilization of industry CHP, biomass residuals comprise approximately 76% of fuels consumed in US pulp and paper industry cogeneration systems.

Operation of CHP systems does increase on-site emissions compared to emissions from stream generation in stand-alone boilers. The increase in on-site GHG emissions from CHP utilization was 4.0 million mt CO_2e in 2018 for the US pulp and paper industry. However, this increase in on-site emissions is more than offset by the reduced need for purchased utility-generated power.

Table A1. *US Pulp and Paper Industry GHG Emissions from Use of CHP Technology in 2018 Compared to the Separate Generation of Heat and Power*

	GHG Emissions (million mt CO_2e)				
Population	CHP Operation	Separate Generation of Electricity[a]	Separate Generation of Steam[b]	Difference in On-site Emissions	Avoided GHG Emissions
Mill-specific Information	20.2	13.9	16.8	3.5	10.5
US Pulp and Paper Industry	23.6	16.2	19.6	4.0	12.2

[a] GHG emissions due to purchase of electricity equivalent to amount generated from CHP operation.

[b] GHG emissions from separate generation of steam to meet process needs, equivalent to amount from CHP operation, and based on the same fuel mix to generate combined heat and power.

Calculation Procedure

Mill-specific environmental and energy data are collected biennially by the American Forest and Paper Association (AF&PA) and by NCASI for US pulp and paper mills. The latest year of quality assured data for the AF&PA/NCASI data set is from 2018 and represents approximately 85% of the total paper, paperboard, and market pulp production in the US. Of the 176 mills in the AF&PA/NCASI database, 97 facilities with combined production of 57.5 million short tons reported 33,143 million kWh of cogenerated electricity in the 2018. These data served as the basis for this cogeneration analysis and are called the “Environmental Health and Safety (EHS) database” throughout this white paper. Mills report total site level energy consumption on a high heating value basis. Only energy consumed in CHP systems (either boiler/steam turbine systems or direct fired turbine systems) should be considered when calculating avoided GHG emissions from CHP. Fuels consumed in lime kilns, mobile sources, incinerators, generators, tissue dryers, etc. should be excluded, as well as fuel consumed in boilers that operate solely for steam production or electricity production. Figure shows a schematic that was followed to translate site level EHS data to a form usable to calculate avoided GHG emissions from CHP systems.

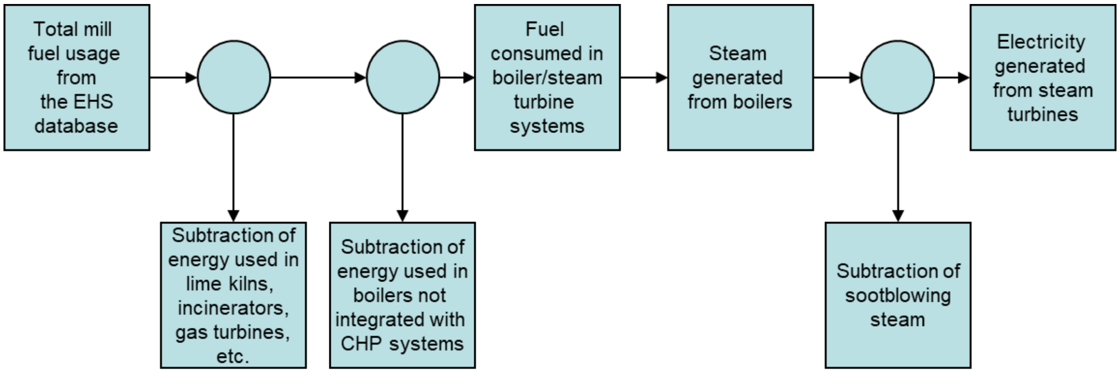

Figure A1. *Schematic Used to Translate EHS Data to Steam and Electricity Generation in Pulp and Paper CHP Systems*

Energy Used in Lime Kilns, Total Reduced Sulfur Incinerators, and Gas Turbines

NCASI maintains a database (latest quality assured information from 2010) of combustion devices for the US pulp and paper industry (NCASI 2010). The NCASI combustion source database was cross-referenced with the EHS database to subtract the energy consumption from lime kilns, TRS incinerators, and gas turbines from total reported mill energy use. Table A2 shows the total energy consumption contributions from lime kilns, TRS incinerators, and gas turbines from facilities that also reported on-site cogeneration.

Table A2. *Energy Consumption from Lime Kilns, TRS Incinerators, and Gas Turbines*

Fuel	Lime Kilns (billion Btu HHV)	TRS Incinerators (billion Btu HHV)	Gas Turbines (billion Btu HHV)
Natural Gas	44,843	1910	8432
Residual Fuel Oil	13,401	100	
Petroleum Coke	3672		
Total Energy Consumption	61,916	2009	8432

HHV=high heating value

Total energy use from mills reporting on-site cogeneration was reduced by subtracting energy consumption from lime kilns, TRS incinerators, and gas turbines at these facilities. It is assumed that the remaining energy is available for cogeneration. Table A3 shows the amount of fuel energy available for cogeneration by fuel type. Approximately 76% of fuels consumed in US pulp and paper industry cogeneration systems are from biomass residuals. It is assumed that reported liquefied petroleum gas, gasoline, kerosene, and minor fossil fuels that fall under the “Other Fuel” or “Other Fuel 1” categories in the EHS database are not used in CHP systems.

Table A3. *2018 Fuels Used for Cogeneration*

Fuel	Cogeneration Fuels[a] (billion Btu)	Cogeneration Fuels (% energy content basis)
Biomass Fuels		
Spent Liquor Solids	759,909	58%
Solid Wood Residuals and Other Biomass Fuels	242,884	18%
Fossil Fuels		
Coal	44,713	3%
Natural Gas	255,449	19%
Rubber Tire Chips	6847	1%
Petroleum Coke	10,084	1%
Sum	**1,319,886**	**100%**

[a] Fuels calculated to be consumed in boiler/steam turbine CHP systems by 2018 EHS survey respondents that reported electrical cogeneration.

The amount of steam production based on cogeneration fuel input is calculated using the boiler thermal efficiencies in Table A4, the properties of superheated high-pressure steam and boiler feedwater in Table A5, and Equation 1. The calculated amount of high-pressure steam generated from the cogeneration fuels in Table A3 was 647,120 million pounds in 2018 (919,826 billion Btu).

Table A4. *Boiler Thermal Efficiencies Based on Fuel Type*

Fuel	Boiler Thermal Efficiency (η)
Spent Liquor Solids	0.65
Solid Wood Residuals and Other Biomass Fuels[a]	0.70
Coal	0.84
Natural Gas	0.80
Rubber Tire Chips	0.80
Petroluem Coke	0.84

[a] Includes all hogged fuels, other biomass, non-recyclable paper, and sludge.

Table A5. *Steam and Feedwater Conditions Used in CHP Analysis*

Stream	Pressure (psig)	Temperature (°F)	Specific Enthalpy[a] (Btu/lb)
High-pressure Steam	1073	860	1421
Medium-pressure Steam	130	386	1213
Low-pressure Steam	36	282	1175
Boiler Feedwater	36	282	251

[a] Verma, Mahendra P. 2003. "Steam Tables for Pure Water as an ActiveX Component in Visual Basic 6.0." *Computers & Geosciences* 29: 1155–1163.

$$F = \eta \cdot \text{Input}/(H_S - H_{FW}) \qquad \text{(Eq. 1)}$$

Where:

F:	flow of high-pressure superheated steam generated from boiler (lb/yr)
η:	boiler energy to steam efficiency (fraction)
Input:	fuel energy input to boiler (Btu/yr)
H_S:	specific enthalpy of high-pressure steam (Btu/lb)
H_{FW}:	specific enthalpy of boiler feedwater (Btu/lb)

Depending on the fuel type, a certain percentage of the high-pressure superheated steam is assumed to be used for soot-blowing purposes. Soot-blowing steam requirements based on fuel type are given in Table A6. After subtracting soot-blowing steam use, the amount of high-pressure steam calculated to be entering steam turbines was 621,235 million pounds in 2018 (883,032 billion Btu).

Table A6. *Soot-blowing Steam Requirements Based on Fuel Type*

Fuel	Steam Generation Used in Soot-blowing (% of High-pressure Steam)
Spent Liquor Solids	6.5
Wood/Bark[a]	2.0
Coal, Petroleum Coke, and Rubber Tire Chips	2.5
Natural Gas	0.0

[a] Includes all hogged fuels, other biomass, and non-recyclable paper.

Power Production from Steam Turbines

Power generated from steam turbines was calculated by using a high-pressure steam to power conversion factor for all cogeneration fuels. This factor is the fraction of high-pressure steam energy content entering a turbine that is converted to electrical power. The conversion factor of 0.12 was tuned (after adjusting for CHP power generated from gas turbines in mills that reported cogeneration) to match the reported 33,143 million kWh of cogenerated electricity in the EHS database. Assuming no energy losses and negligible energy content in any condensates, the high-pressure steam to power conversion factor of 0.12 translates to a power to steam ratio of 0.14 (equivalent to 40 kWh/GJ of steam generated). Power to steam ratios for the pulp and paper industry range from 0.07–0.25 for back-pressure steam turbines and 0.1–0.5 for condensing turbines (Strickland and Nyober 2002).

Gas Turbines

The amount of natural gas consumed in gas turbines from mills that reported both cogenerated electricity and a gas turbine installation is 8,432 billion Btu (Table **A**A2). The fuel consumption, electricity generation, and performance parameters for a gas turbine generator, heat recovery steam generator (HRSG), and extraction condensing steam turbine generator system are taken from McCann (2002) and are used to calculate steam and electricity generation from gas turbines.

Avoided GHG Emissions from CHP

Avoided GHG emissions due to CHP technology are calculated by comparing emissions from the separate generation of heat and power to those from combined generation of heat and power. From a process standpoint, steam of pressure higher than 10 to 12 bar (typically referred to as medium-pressure steam) is not needed. On-site GHG emissions from mills generating high-pressure steam that is subsequently expanded within a turbine for power generation and extracted for process needs will be higher than those from a mill generating medium-pressure steam in a HRSG and pressure reducing a portion of it to meet low-pressure steam requirements. Figures A2 and A3 show schematics for generating the same amounts of electricity and steam in a CHP system and separately.

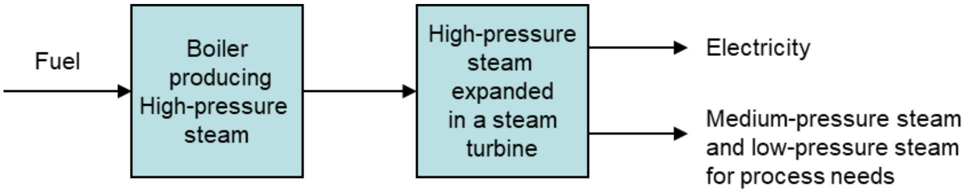

Figure A2. *Steam and Electricity Generation in a CHP System*

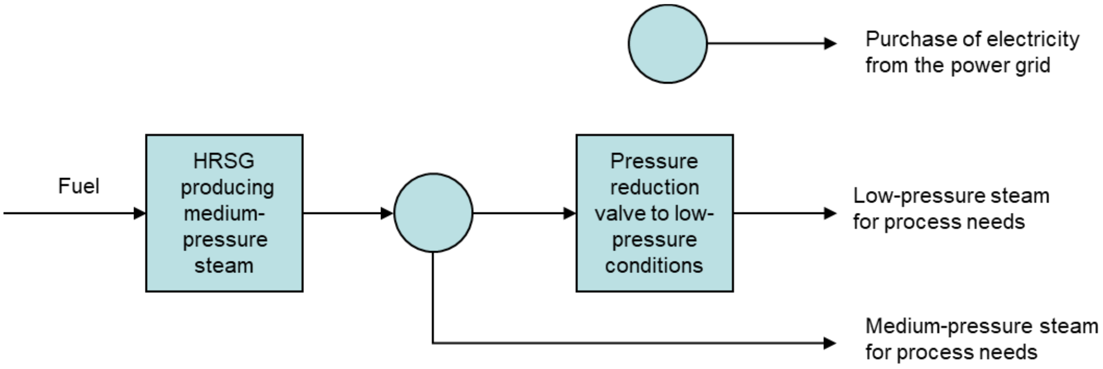

Figure A3. *Separate Generation of Steam and Electricity (same amounts as in Figure)*

GHG emissions from steam and electricity generated in CHP systems are calculated based on fuel amounts used in cogeneration (Table A3), natural gas used in gas turbines (Table **A**A2), and IPCC and World Resources Institute (WRI)/World Business Council for Sustainable Development (WBCSD) fuel-specific emission factors and global warming potentials. Fuel-specific emission factors and global warming potentials from the IPCC (IPCC 2006) were used, with the exception of those for CH_4 and N_2O from biomass combustion, where factors from WRI/WBCSD (2005) were used. The total GHG emissions calculated in this fashion are 20.2 million mt CO_2e/yr. GHG emissions from the purchase of an equivalent amount of grid electricity as self-generated CHP electricity (33,143 million kWh) is calculated using the US average grid power emission intensity value of 0.432 mt CO_2e/MWh[13] and results in GHG emissions of 13.9 million mt CO_2e/yr. The fuel energy needed to generate an equivalent amount of steam as that produced in CHP systems (647,120 million pounds) is calculated using enthalpies for medium-pressure steam and feedwater (Table A5), boiler thermal efficiencies (Table A4), Equation 2 (a rearranged form of Equation 1), and steam mass flows from cogeneration fuels.

$$\text{Input} = F \cdot (H_\text{S} - H_\text{FW})/\eta \qquad \text{(Eq. 2)}$$

GHG emissions from separate generation of steam are 16.0 million mt CO_2e/yr. Avoided GHG emissions from CHP operation are calculated by summing the emissions attributed to purchased electricity and the separate generation of steam minus emissions from CHP operation. Avoided GHG emissions from all mills in the EHS database that reported cogenerated electricity are 10.5 million mt CO_2e/yr.

Scale-Up to Total US Production

The scale-up of avoided emissions calculated from the EHS database to total US pulp and paper production was accomplished by ratioing total in-plant cogeneration reported in the 2018 US Energy Information Administration (EIA) Manufacturing Energy Consumption Survey (MECS)[14], which is assumed to have complete coverage for the sector, to in-plant cogeneration reported by facilities in the EHS database. In-plant cogeneration from the 2018 EIA MECS was 38,663 million kWh and in-plant cogeneration from facilities from the EHS database was 34,059 million kWh. The ratio of 38,663 to 33,143 (scaling factor 1.17) was used to scale results to the US pulp and paper sector in Table A1.

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[13] https://www.epa.gov/egrid

[14] US EIA MECS: "Table 11.3 Electricity: Components of Onsite Generation, 2018." https://www.eia.gov/consumption/manufacturing/data/2018/pdf/Table11_3.pdf

Appendix A References

IPCC (Intergovernmental Panel on Climate Change). 2006. *2006 IPPC Guidelines for National Greenhouse Gas Inventories*, edited by Simon Eggleston, Leandro Buendia, Kyoko Miwa, Todd Ngara, and Kiyoto Tanabe. IPCC National Greenhouse Gas Inventories Programme. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

McCann, Derek. 2002. A Review of the Applications of Gas Turbine Generators to the Pulp and Paper Industry. *Pulp & Paper Canada*. 103, no. 1:T12–T15.

NCASI (National Council for Air and Stream Improvement, Inc.). July 2005. Calculation Tools for Estimating Greenhouse Gas Emissions from Pulp and Paper Mills. Version 1.1. The Climate Change Working Group of The International Council of Forest and Paper Associations (ICFPA). Research Triangle Park, N.C.: NCASI. https://ghgprotocol.org/sites/default/files/2023-03/Pulp_and_Paper_Guidance.pdf.

———. 2010. *Combustion Source Database*. Research Triangle Park, N.C.

———. 2021. *Greenhouse Gas Reductions for the US Pulp and Paper Industry*. White Paper WP-21-07. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

Strickland, Cathy, and John Nyober. 2002. Cogeneration Potential in Canada Phase 2. Report for Natural Resources Canada. MK Jaccards and Associates.

Appendix B: LCA Methodology and System Boundaries used in NCASI LCA Studies

In detailed cradle to final energy use life cycle studies on the GHG and fossil fuel reduction benefits of using biomass residuals for energy production (NCASI 2011; Gaudreault et al. 2012; NCASI 2014; NCASI 2017), life cycle GHG emissions were determined for biomass residual fuels used in the US forest products sector. The LCA methodology and system boundaries used in the NCASI studies are provided below.

Methodology

Life cycle assessment (LCA) is the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle,” the life cycle being “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal” (ISO 2006a, p. 2).

LCA principles and methodology are framed by a set of standards (ISO 2006a, 2006b) and technical report and specification (ISO 2002, 2012a, 2012b) from the International Organization for Standardization (ISO). ISO describes LCA methodology in four phases:

1) **Goal and scope definition,** in which the aim of the study, the product system under study, its function and functional unit, the intended audience, and the methodological details on how the study will be performed are defined;
2) **Life cycle inventory analysis,** which is the “phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 2006a, p. 2);
3) **Life cycle impact assessment (LCIA),** which is the “phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 2006a, p. 2); and
4) **Life cycle interpretation,** which is the “phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 2006a, p. 2).

The NCASI LCA studies:

- used widely accepted LCA concepts, such as those described in LCA ISO standards 14040 and 14044 (ISO 2006a, 2006b);
- were built on the approaches by others [e.g., US Environmental Protection Agency (US EPA), Consortium for Research on Renewable Materials (CORRIM)];
- were based on known and established competitive materials and alternative fates for biomass residuals; and
- did not consider any “export” of the residuals outside the forest products industry (e.g., to utilities).

Streamlining generally can be accomplished by limiting the scope of the study or simplifying the modeling procedures, thereby limiting the amount of data or information needed for the assessment (Todd and Curran 1999). In these studies, two main streamlining approaches were taken: limiting the impact assessment to two indicators (global warming and fossil fuel consumption), and for the most part, using generic information. Because of streamlining, these studies do not fully comply with ISO 14044 requirements for comparative assertions disclosed publicly. However, these studies align as much as possible with ISO 14044.

System Boundaries

For each of the biomass systems examined (spent liquor solids, woody mill residuals, waste water treatment plant (WWTP) residuals, paper recycling residuals, and forest harvest residuals), two alternative systems were compared:

1) Biomass Energy System: Production of 1 GJ of energy (heat or CHP) using manufacturing residuals.

2) Non-Use System: Production of 1 GJ of energy (in the same form as in #1) using fossil fuels and alternative fate of the residuals.

Schematically, the two compared systems are shown in Figure B4 (in this case for the forest harvest residuals case). In addition to the cases where 1 GJ of energy was assumed to be produced from fossil fuels, an additional scenario was considered where only the alterative fate of the studied residual was modelled from an LCA perspective. Schematically, the scenario where only the alterative fate of the studied residual was modelled (excluding any GHG or energy impact from fossil fuel displacement) is shown in Figure B5. For the spent liquor solids study, the biomass energy system and non-use system were compared as with the other biomass residuals. In addition to energy generation, the utilization of spent liquor solids by the pulp and paper sector in the kraft recovery process regenerates pulping chemicals for reuse, and effectively manages the spent pulping liquor solids. For spent liquor solids, in addition to modelling the alternative fate of spent liquor solids, an alternative mode to generate pulping chemicals was considered in the LCA calculations, and schematically this scenario if provide in Figure B6.

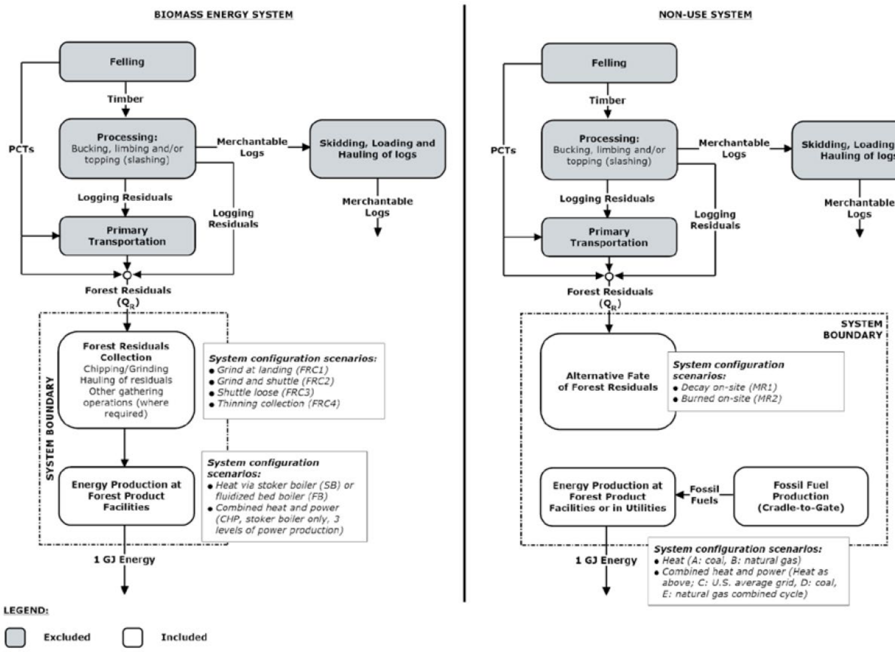

***Figure B4**. System Boundary of the Compared Product Systems (Cradle-to-Final Energy)*

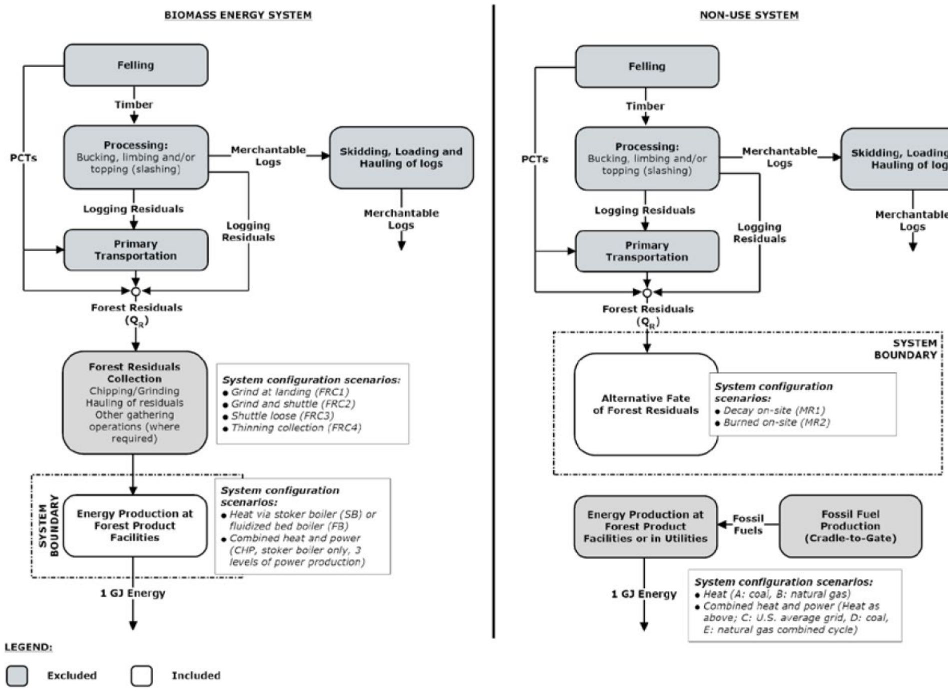

***Figure B5**. System Boundary of the Compared Product Systems (Gate-to-Gate) Fossil Fuel Displacement Not Considered for Energy Generation*

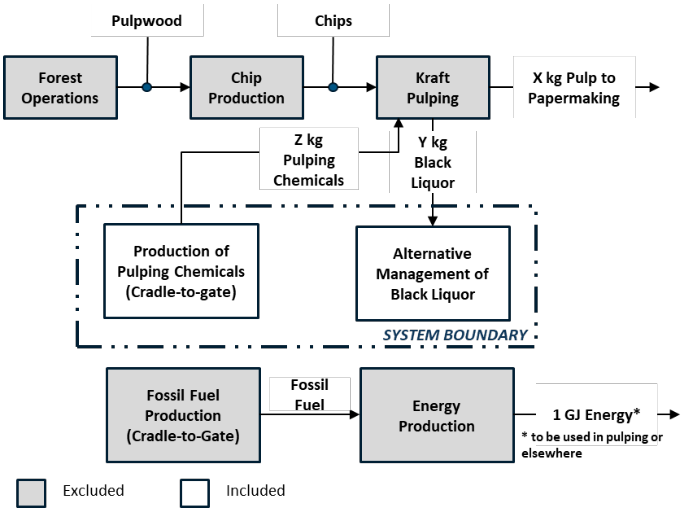

Figure B6. *Spent Liquor Solids System Boundary of the Compared Product Systems (Gate-to-Gate) Fossil Fuel Displacement Not Considered for Energy Generation*

Appendix B References

Gaudreault, Caroline, Barry Malmberg, Brad Upton, and Reid Miner. 2012. "Life Cycle Greenhouse Gases and Non-Renewable Energy Benefits of Kraft Black Liquor Recovery." *Biomass and Bioenergy* 46:683–692. https://doi.org/10.1016/j.biombioe.2012.06.027.

International Organization for Standardization (ISO). 2002. Environmental management - Life cycle assessment - Data documentation format. ISO/TS 14048. Geneva: International Organization for Standardization. https://www.iso.org/standard/29872.html

———. 2006a. Environmental management - Life cycle assessment - Principles and framework. ISO 14040. Geneva: International Organization for Standardization. https://www.iso.org/standard/37456.html

———. 2006b. Environmental management - Life cycle assessment - Requirements and guidelines. ISO 14044. Geneva: International Organization for Standardization. https://www.iso.org/standard/38498.html

———. 2012a. Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations. ISO/TR 14047. Geneva: ISO. https://www.iso.org/standard/57109.html

———. 2012b. Environmental management — Life cycle assessment — Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis. ISO/TR 14049. Geneva: ISO. https://www.iso.org/standard/57110.html

NCASI (National Council for Air and Stream Improvement, Inc). April 2011. Greenhouse Gas and Non-Renewable Energy Benefits of Black Liquors Recovery. Technical Bulletin No. 984. Research Triangle Park, N.C.

———. October 2013 (revised August 2014). Greenhouse gas and fossil fuel reduction benefits of using biomass manufacturing residuals for energy production in forest products facilities. Technical Bulletin No. 1016. Research Triangle Park, N.C.

———. 2017. Greenhouse Gas Aspects of Using Forest Residuals for Energy Production in Forest Products Facilities. Technical Bulletin No. 1042. Research Triangle Park, N.C.

Todd, J.A. and Curran, M.A. 1999. Streamlined life-cycle assessment: A final report from the SETAC North America Streamlined LCA Workgroup. Pensacola, FL: Society for Environmental Toxicology and Chemistry (SETAC).

Appendix C: CHP GHG Allocation Approaches for the Pulp and Paper Industry

Introduction

CHP is an energy efficient mode of steam and electricity generation, and the US forest products industry is a leader in the utilization of CHP for industrial energy generation. In 2018, the US forest products industry produced 30% of all CHP power generated by manufacturing industries: 38,663 million kWh total, 5,372 million kWh of which was sold to the electrical grid[15].

Since CHP systems generate steam and electricity simultaneously or sequentially, allocation approaches have been developed to allocate the GHG emissions derived from the combustion of fuels to the multiple products (steam and electricity). Overviews on CHP allocation approaches are reviewed and developed in several publications (Nyober and Groves 2012; Strickland and Nyober 2002; Strickland Nyober 2004; Phylipsen et al. 1998; Rosen 2008; WRI/WBCSD 2006). Within this white paper, CHP GHG allocation approaches are summarized, and allocation approaches are applied to characteristic CHP energy generation in the US pulp and paper sector to determine typical GHG allocation factors for steam and electricity. Properties of characteristic CHP energy generation for the US pulp and paper sector were developed in a companion NCASI memo "Avoided Greenhouse Gas Emissions from the Use of Combined Heat and Power in the US Pulp and Paper Industry."

Summary of Approaches

Table C1 shows the variation of fractional allocation amounts by method for the US pulp and paper sector. Figure shows the results of Table C1 in graph form.

Table C1. *Variation of Fractional Allocation Amounts by Method*

Allocation Method	f_E	f_Q
Energy Content	0.13	0.87
Incremental Fuel Consumption (Electricity)	0.21	0.79
Work Potential Method	0.22	0.78
Incremental Fuel Consumption (Steam)	0.24	0.76
Simplified Efficiency Method	0.26	0.74
Economic Value Method	0.29	0.71

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[15] US EIA MECS Survey Data. https://www.eia.gov/consumption/manufacturing/data/2018/

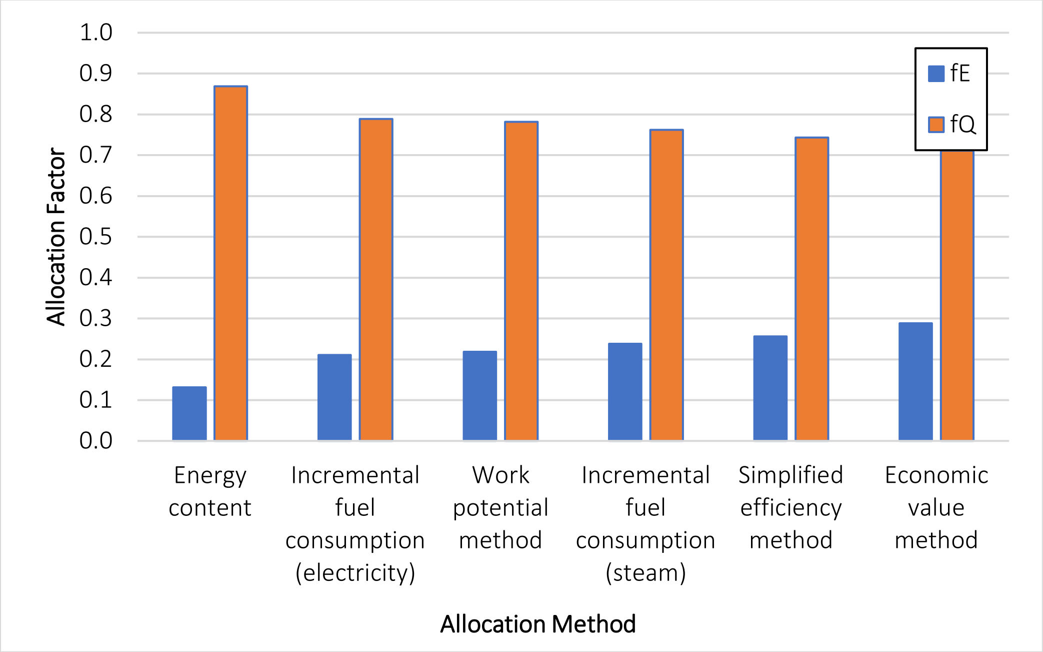

Figure C7. *Variation of Fractional Allocation Amounts by Method*

Allocation Based on Energy Content of Products

Allocation based on energy content of products allocates GHG emissions according to the quantities of energy contained in each CHP output stream. The advantage of this allocation approach is that it is straightforward and based only on operational outputs. The disadvantage of this approach is that it is based on quantity of energy versus quality of energy.

$$f_E = P/(P+Q)$$

$$f_Q = Q/(P+Q)$$

Where

f_E: fraction of cogeneration emissions allocated to electricity

f_Q: fraction of cogeneration emissions allocated to steam

P: Delivered electricity generation

Q: Steam output

The Simplified Efficiency Method

The simplified efficiency method allocates GHG emissions according to the amount of fuel energy used to produce each final energy stream. The efficiency method is the preferred method in the WRI/WBCSD (2006) guidance on allocation of GHG emissions from CHP systems.

$$f_E = (P/\varepsilon_P)/\left(P/\varepsilon_P + Q/\varepsilon_Q\right)$$

$$f_Q = \left(Q/\varepsilon_Q\right)/\left(P/\varepsilon_P + Q/\varepsilon_Q\right)$$

Where:

f_E: fraction of cogeneration emissions allocated to electricity

f_Q: fraction of cogeneration emissions allocated to steam

ε_P: efficiency of electricity generation (in the absence of measures of efficiency, typically assume 0.35). The average electrical generation efficiency from coal, nuclear, natural gas, and petroleum fuel sources in the US in 2018 was 0.35. The average electrical generation efficiency from natural gas in the US in 2018 was 0.44.[16]

ε_Q: efficiency of steam generation (in the absence of measures of efficiency, typically assume 0.8). The steam generation efficiency of 0.8 is typical of a natural gas fired power boiler. Thermal efficiencies of other fuels used in the pulp and paper industry are provided in Table C2.

P: delivered electricity generation

Q: steam output

Table C2 shows typical thermal efficiencies for boilers firing different fuels. The efficiencies listed in Table C2 can be used for ε_Q in the simplified efficiency method in the absence of site-specific data.

Table C2. *Literature with Published Thermal Efficiencies for Fuel Type Common in the Pulp and Paper Sector*

Fuel	Efficiency	Reference
Spent Liquor Solids	61[a]	Adams (1997)
Spent Liquor Solids	68-69	AGRA (1998)
Hogged Fuel	67	AGRA (1998)
Natural Gas	83	AGRA (1998)
Oil	87	AGRA (1998)
Sludge	65	AGRA (1998)
Spent Liquor Solids and Biomass	64[b]	Francis (2006)
Coal	85, 75[c]	CBIO (2003)
Oil	80, 72[c]	CBIO (2003)
Gas	75, 70[c]	CBIO (2003)
Biomass	70, 60[c]	CBIO (2003)

[a] Includes soot-blowing 3.4% and boiler blowdown 0.85%.
[b] Canadian average.
[c] Second number is low load efficiency, numbers are for relatively new units at the time of publication (2003).

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[16] US EIA, Form EIA-923, "Power Plant Operations Report," and predecessor form(s) including US EIA, Form EIA-906, "Power Plant Report;" and Form EIA-920, "Combined Heat and Power Plant Report;" Form EIA-860, "Annual Electric Generator Report."

Work Potential Method

The work potential method allocates GHG emissions based on the useful work that can be performed by the heat and electric power.

$$f_E = \mathrm{W}_P/(\mathrm{W}_P + \mathrm{W}_Q)$$

$$f_Q = \mathrm{W}_Q/(\mathrm{W}_P + \mathrm{W}_Q)$$

It is typically assumed the the conversion efficiency of electrical energy to mechanical work is 1 (100%).

$$\mathrm{W}_P = P$$

For thermal—e.g., steam—to mechanical work conversion, Carnot's theorem states that no engine operating between two heat reservoirs can be more efficient than a Carnot engine operating between the same reservoirs.

$$\eta_T = \frac{W_Q}{Q} = 1 - \frac{T_C}{T_H}$$

Where:

η_T:	the maximum efficiency or Carnot efficiency
W_P:	the work potential by the system from electricity
W_Q:	the work potential by the system from heat
Q:	heat into the system
T_C:	absolute temperature of the cold reservoir
T_H:	absolute temperature of the hot reservoir

Applying Carnot's theorem, the heat work potential becomes:

$$\mathrm{W}_Q = Q\eta_T = Q(1 - T_C/T_H)$$

Superheated steam temeprature trends for the pulp and paper industry have increased over time (NCASI 2019). The choice of cold temperature reservoir influences the Carnot efficiency used in the work potential method. Table C3 shows efficiencies for various superheated steam tempatures, assuming the cold reservoir temperature is a typical return condensate temperature of 95°C.

Table C3. *Carnot Efficiencies for the Work Potential Method*

Superheated Steam Temperature (K)	η_T
723	0.49
773	0.52
798	0.54

The allocation fractions can be given in terms of the steam and electricity energy amounts and the temperatures of the hot and cold resevoir:

$$f_E = P/\left(P + Q(1 - T_C/T_H)\right)$$

$$f_Q = Q(1 - T_C/T_H)/\left(P + Q(1 - T_C/T_H)\right)$$

Or in terms of the Carnot efficiency:

$$f_E = P/(P + Q\eta_T)$$

$$f_Q = Q\eta_T/(P + Q\eta_T)$$

Allocation Based on Economic Value of Products

The economic approach allocates GHG emissions based on the economic value of the electricity and steam produced:

$$f_E = \$_P P/\left(\$_P P + \$_Q Q\right)$$

$$f_Q = \$_Q Q/\left(\$_P P + \$_Q Q\right)$$

In terms of the ratio of $\$_P/\$_Q$:

$$f_E = P/\left(P + Q/\left(\$_P/\$_Q\right)\right)$$

$$f_Q = Q/\left(P \cdot \left(\$_P/\$_Q\right) + Q\right)$$

Average industrial electricity costs, $\$_P$, can be found in EIA's Electric Power Monthy[17]. Average steam costs may be calculated using natural gas as the fuel for steam generation. Natural gas prices may be taken from Henry Hub natural gas prices[18], and natural gas boiler thermal efficiencies are given in Table C2.

Allocation Based on Incremental Fuel Consumption for Electrical Production

The allocation approach based on incremental fuel consumption for electrical production considers steam the primary product and electricity as a secondary product. In this approach, fuel use associated with steam generation is calculated based on a stand-alone steam generation device, i.e., a reference boiler. The fuel use attributed to electricity is calculated as the difference between CHP fuel use and the fuel use calculated from the reference boiler.

$$F_Q = Q/\varepsilon_Q$$

$$F_E = F - F_Q$$

$$f_Q = Q/\left(F \cdot \varepsilon_Q\right)$$

$$f_E = 1 - f_Q$$

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[17]. US EIA. Electris Power Monthly: Table 5.6.A. Average Price of Electricity to Ultimate Customers by End-Use Sector. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

[18] US EIA. Natural Gas: Henry Hub Natural Gas Spot Price. https://www.eia.gov/dnav/ng/hist/rngwhhdm.htm

Where:

f_E: fraction of cogeneration emissions allocated to electricity

f_Q: fraction of cogeneration emissions allocated to steam

ε_P: efficiency of electricity generation (in the absence of measures of efficiency, typically assume 0.35). The average electrical generation efficiency from coal, nuclear, natural gas, and petroleum fuel sources in the US in 2018 was 0.35. The average electrical generation efficiency from natural gas in the US in 2018 was 0.44.[19]

ε_Q: efficiency of steam generation (in the absence of measures of efficiency, typically assume 0.8). The steam generation efficiency of 0.8 is typical of a natural gas fired power boiler. Thermal efficiencies of other fuels used in the pulp and paper industry are provided in Table C2.

P: delivered electricity generation

Q: steam output

F: fuel input to the cogeneration system

F_E: fuel use attributed to electricity generation

F_Q: fuel use attributed to steam generation

Allocation Based on Incremental Fuel Consumption for Steam Production

The allocation approach based on incremental fuel consumption for steam production considers electricity the primary product and steam generation a secondary product. In this approach, fuel use associated with electricity generation is calculated based on a stand-alone electricity generation device, i.e., a reference power plant. The fuel use attributed to steam is calculated as the difference between CHP fuel use and the fuel use calculated from the reference power plant.

$$F_P = P/\varepsilon_P$$

$$F_Q = F - F_P$$

$$f_E = P/(F \cdot \varepsilon_P)$$

$$f_Q = 1 - f_P$$

Where:

f_E: fraction of cogeneration emissions allocated to electricity

f_Q: fraction of cogeneration emissions allocated to steam

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[19] US EIA, Form EIA-923, "Power Plant Operations Report," and predecessor form(s) including US EIA, Form EIA-906, "Power Plant Report;" and Form EIA-920, "Combined Heat and Power Plant Report;" Form EIA-860, "Annual Electric Generator Report."

ε_P: efficiency of electricity generation (in the absence of measures of efficiency, typically assume 0.35). The average electrical generation efficiency from coal, nuclear, natural gas, and petroleum fuel sources in the US in 2018 was 0.35. The average electrical generation efficiency from natural gas in the US in 2018 was 0.44.[20]

ε_Q: efficiency of steam generation (in the absence of measures of efficiency, typically assume 0.8). The steam generation efficiency of 0.8 is typical of a natural gas fired power boiler. Thermal efficiencies of other fuels used in the pulp and paper industry are provided in Table C2.

P: delivered electricity generation

Q: steam output

F: fuel input to the cogeneration system

F_E: fuel use attributed to electricity generation

F_Q: fuel use attributed to steam generation

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[20] US EIA, Form EIA-923, "Power Plant Operations Report," and predecessor form(s) including US EIA, Form EIA-906, "Power Plant Report;" and Form EIA-920, "Combined Heat and Power Plant Report;" Form EIA-860, "Annual Electric Generator Report."

Appendix C References

Adams, Terry N., William James Frederick, Thomas M. Grace, Mikko Hupa, Kristiina Iisa, Andrew K. Jones, and Honghi Tran. 1997. *Kraft Recovery Boilers.* American Forest & Paper Association Atlanta, GA: Tappi Press.

AGRA Simons and Pulp and Paper Technical Association of Canada. 1998. *A Guide to Energy Savings Opportunities in the Kraft Pulp Industry*. AGRA Simons Limited: Vancouver, BC; Pulp and Paper Technical Association of Canada: Brossard, QC.

CIBO (Council of Industrial Boiler Owners). 2003. Energy Efficiency and Industrial Boiler Efficiency: An Industry Perspective. https://invenoinc.com/wp-content/uploads/2017/05/CIBO-Steam-System-Efficiency-and-Boilers.pdf.

Francis, Bill, Michael Towers, and Tom Browne. 2006. “Benchmarking Energy Use in Pulp and Paper Operations”. 92nd Pulp and Paper Technical Association of Canada Annual Meeting: Montréal, QC.

NCASI (National Council for Air and Stream Improvement, Inc.). 2019. General Trends in Pulp and Paper Boiler Development. Technical Memorandum.

Nyober, John, and Steve Groves. 2008. A Review of Existing Cogeneration Facilities in Canada. Report by Canadian Industrial Energy End-Use Data and Canalysis Center (CIEEDAC). Burnaby, BC: Simon Fraser University.

Nyober, John, and Steve Groves, S. 2012. A Review of Existing Cogeneration Facilities in Canada. Report by Canadian Industrial Energy End-Use Data and Canalysis Center (CIEEDAC). Burnaby, BC: Simon Fraser University.

Strickland, Cathy, and John Nyober. 2002. Co-generation Potential in Canada Phase 2. Report for Natural Resources Canada. MK Jaccards and Associates.

Strickland, Cathy, and John Nyober. 2004. A Review of Existing Cogeneration Facilities in Canada. Report by Canadian Industrial Energy End-Use Data and Canalysis Center (CIEEDAC). Burnaby, BC: Simon Fraser University.

Phylipsen, G. J. M., Kornelis Blok, Ernst Worrell. 1998. *Handbook on International Comparisons of Energy Efficinecy in the Manufacturing Industry*. Netherlands: Department of Science, Technology and Society, Utrecht Universty.

Rosen, Marc A. 2008. Allocating Carbon Dioxide Emission from Cogeneration Systems: Descriptions of Selected Output-based Methods. *Journal of Cleaner Production*. 16, no. 2: 171–177. https://doi.org/10.1016/j.jclepro.2006.08.025.

World Resources Institute (WRI) / World Business Council for Sustainable Development (WBCSD). 2006. Allocation of GHG Emissions from a Combined Heat and Power (CHP) Plant: Guide to Calculation Worksheets (September 2006) v1.0: A WRI/WBCSD GHG Protocol Initiative Calculation Tool. https://ghgprotocol.org/sites/default/files/ghgp/CHP_guidance_v1.0.pdf