Report on

A Life Cycle Analysis of the Sawmilling Process of the Thompson Appalachian Hardwood Facility

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Acknowledgments

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Abbreviations

USA	United States of America
USD	United States Dollar
LCA	Life Cycle Analysis
GHG	Green House Gas(ses)
BF	Board Feet
m^3	Cubic meter
GWP	Global Warming Potential
lb	Pounds
CO2eq	Carbon Dioxide Equivalents
FFD	Fossil Fuel Depletion
FW	Consumption of Freshwater Sources
gal	Gallons
TAH	Thompson Appalachian Hardwood
DQI	Data Quality Indicator
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Analysis
PFD	Process Flow Diagram
MS	Microsoft
yr	Year
MWh	Megawatt-hour
MJ	Megajoule
kWh	Kilowatt-hour
kg	Kilogram
CORRIM	Consortium for Research on Renewable Industrial Materials
HHV	Higher Heating Value
LHV	Lower Heating Value
MC	Moisture Content
wb	Wet Basis
db	Dry Basis

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Executive Summary

This report contains an analysis of onsite energy consumption and carbon emissions at the Thomson Appalachian Hardwoods sawmill. A Life Cycle Analysis (LCA) approach was used, with a functional unit of one year's worth of lumber production. The system includes all biomass flows between incoming logs and material marked ready for sale.

This report followed the ISO 14040 standard, which consists of four phases: goal & scope, inventory analysis, impact analysis, and interpretation. Goal & scope define the framework for the analysis. Mass and energy flows within the system were determined with minimal assumptions based on company data from 2023 (where possible). These were used to determine the carbon emissions for each stage of the process and then interpreted.

The scenario was that of a sawmill operating kilns fueled by a mix of biomass residue and propane combustion. In the results, there is also a comparison to theoretical sequestered below ground carbon during tree cultivation to highlight the reduced emissions from the process. The most significant driver of carbon emissions was the kiln drying process, making up 76.35% of the total 2015.34 tons of carbon emitted. Transportation and sorting of material was the second highest contributor, making up 8.93%.

Total energy use (including electric and fuel combustion) was composed of 24.41% fossil-fuel energy sources. Renewable sources comprised 73.49% of total energy use (Figure 3).

Options to further reduce emissions from fossil fuel sources include improving kiln efficiency by reducing air leakage, optimizing fan venting and heat recovery, and regularly measuring the moisture content of green lumber. Sensitivity analysis indicated a degree of reactivity on water content, that impacts biodegradation and drying, rates. Operations can also be altered/optimized to reduce travel distance within the facility and therefore reduce diesel consumption.

The scope of this work is a gate-to-gate analysis, including all biomass flows between incoming logs and wood products ready for sale. Therefore, it is suggested that further study of a cradle-to-gate LCA, to include the cultivation of logs, be carried out. Using biomass to replace fossil fuels can displace and avoid carbon emissions when accounting for sequestered carbon from regenerative forestry.

1. Background

Global demand for wood materials is projected to double from 2022 to 2060 in the USA alone.[1] The wood products industry output does not currently match the demand for wood products in the USA. As of 2020, $44,580 million USD worth of material is imported yearly, 42.4% of which is from Canada.[2] Wood is used for several products that Americans consume daily and converting wood from forests into consumable products such as lumber, paper, or furniture involves various processes that move, process, and change the wood and its properties.[3] This requires energy consumption and results in transformation of the product's mass. These vital products will continue to be distributed for use. Understanding the carbon life cycle and carbon emissions associated with processing wood into a desired product, such as lumber, is important. As a large industry, efficiency during production is required, and it is crucial for mitigating the negative externalities of production and supporting effective decision-making to reduce environmental impacts. Sawmills directly impact the industry via lumber manufacturing and jobs created at the facility. In addition, indirect impacts include job creation for timber cultivators and truckers, while induced impacts include overall economic stability particularly for rural communities. The sustainable wood products market is growing. Currently valued at approximately $150 billion, it is expected that the industry will reach a value of $250 billion by 2033.

Life Cycle Analysis (LCA) is a standardized method of assessing environmental impacts of a product or process. This is a system that is useful in many industries, including for the purposes of assessing the environmental impacts of producing hardwood boards in sawmills. LCA highlights the benefits of renewables over fossil fuels and is frequently used as a tool to provide policy and financial incentives for transitioning to renewable and sustainable energy sources.[4]

It is important to understand how each industry impacts global emissions in order to direct future actions in a way to mitigate effects. Carbon from anthropogenic activities has contributed to approximately 80% of all global GHG emissions.[5] Despite this, the wood products industry is potentially less energy intensive when compared to the processing of other common building materials, brick, steel, concrete and aluminum processing. The cultivation of wood is less energy intensive, and timberlands serve as carbon sinks. Producing other building materials is associated with more carbon emissions.[6] A meta-analysis that spans from 1990 to 2005 found that the US forest sector sequestered an average of $1.79x10^{11}$ tons of carbon per year. Live and dead trees accounted for 49% of this, wood products in landfills 27%, and down dead wood, wood products in use, and the forest floor and soil, the remainder. Thus, consideration of sequestered carbon during cultivation should be noted.[7]

It is known that the Average US hardwood sawmill production is that of 7.6 million board feet (BF). Larger facilities average about 11.7 million board feet (BF), and large facilities can range in production from 1.6 million BF – 54.0 BF.[8] The lumber production process produces a significant volume of milling residues which can be utilized for energy in kiln drying or electricity generation to substitute the energy needs of the facility.[9] An LCA can help estimate the avoided emission with the substitution of biomass for fossil fuels.

An individual LCA provides individualized approaches for emissions estimation.[10] The production of 1 m^3 (423.8 BF) of hardwood in the US north/northeast results in a GWP of 366.67 Ib CO2 eq, a FFD (Fossil Fuel Depletion) of 98.99 kWh surplus, and a FW (consumption of freshwater resources) of 144.04 gal.[11] Important data to gather but is a source that does not come close to matching the geographic region and tree species mix as our scenario outlines. Another study found that the production of 1 m^3 (423.8 BF) of green hardwood in New Brunswick, Canada results in a GWP of 89.68 Ib CO2 eq and a FFD of 162.13 kWh, again this does not match the scope of our study.[12]

With regulatory restrictions and incentives coming along, now is the time to carry out region-specific studies for more information for best practice decision-making.[3] The Tennessee Volunteer Emission Reduction Strategy is an emissions reduction plan which aims to provide incentives for investment in technologies that reduce total GHG emissions. One specific area proposed is that of renewable energy generation.[13]

There are some examples of LCA studies carried out on the topic of hardwood lumber processing but not at any scale such as that of a facility like Thompson Hardwood Appalachian. This is a large-scale facility and understanding the exact profile of the wood products industry is very difficult due to supply chain, processing, and forest carbon modeling. Sawmill operations vary in scale and thus more specific models allow for greater accuracy.[14]

The goal is to evaluate the environmental impacts of hardwood milling in Tennessee using Life Cycle Assessment to estimate the Global Warming Potential (GWP) in the form of carbon emissions for the hardwood sawmill process in a gate-to-gate analysis (Figure 1).

2. Scope of the study

The sawmill aims to track Greenhouse Gas (GHG) emissions, specifically carbon, and utilize the woody residues produced by the mill as waste (mill residues) within its processing system. Typically, the mill residues, including the shavings and bark, are either sold to other facilities or sent to landfills, which is associated with emissions via transportation and biodegradation into its constituent elements (carbon, oxygen, and hydrogen) depending upon where it ends up as final use. Instead, TAH uses an onsite combustion system that creates steam to kiln dry material. Utilizing this within the facility avoids emissions and helps manage residues onsite, where a portion of carbon will be sequestered as well as fueling the sawmill processes and reducing emissions through lessened petroleum use. Hence, we designed this study to evaluate the environmental impacts measured as GHG potential for a scenario that replaces a portion of diesel fuel and propane (natural gas) with heat biomass combustion to use residues and reduce emissions during lumber kiln drying.

The scope of this study includes what is in the system boundary (Figure 1) and is a gate-to-gate analysis of the sawmill. Here, a combination of biomass combustion, along with diesel powered kilns for wood drying is used. within the Southeastern USA, and a time horizon of one year. Greenhouse gas emissions were selected as the environmental impacts, primarily determined by CO2 emissions from the process. A functional unit is defined as the carbon emissions from one year of production of hardwood lumber from incoming logs (Figure 1).

3. Methodology & Materials

The LCA methodology for the hardwood sawmill facility follows the ISO 14040 standard. This international standard provides the framework to carry out LCAs. The standard outlines four main steps: (1) Goal and Scope of LCA, (2) Life Cycle Inventory (LCI) Assessment, (3) Life Cycle Impact Assessment (LCIA), and (4) Interpretation.

3.1. Data

Data were collected by personal communication with Thompson Appalachian Hardwood, (through the form of billing receipts, gauge readings, and grid electricity reports) with comparisons to relevant literature. Data were utilized based on its publication date and completeness. Seeing as no data were available from 2025 and some data from 2024 was incomplete, data were drawn from 2023 when needed. Data quality was assessed using the DQI method outlined by Weidema.[15]

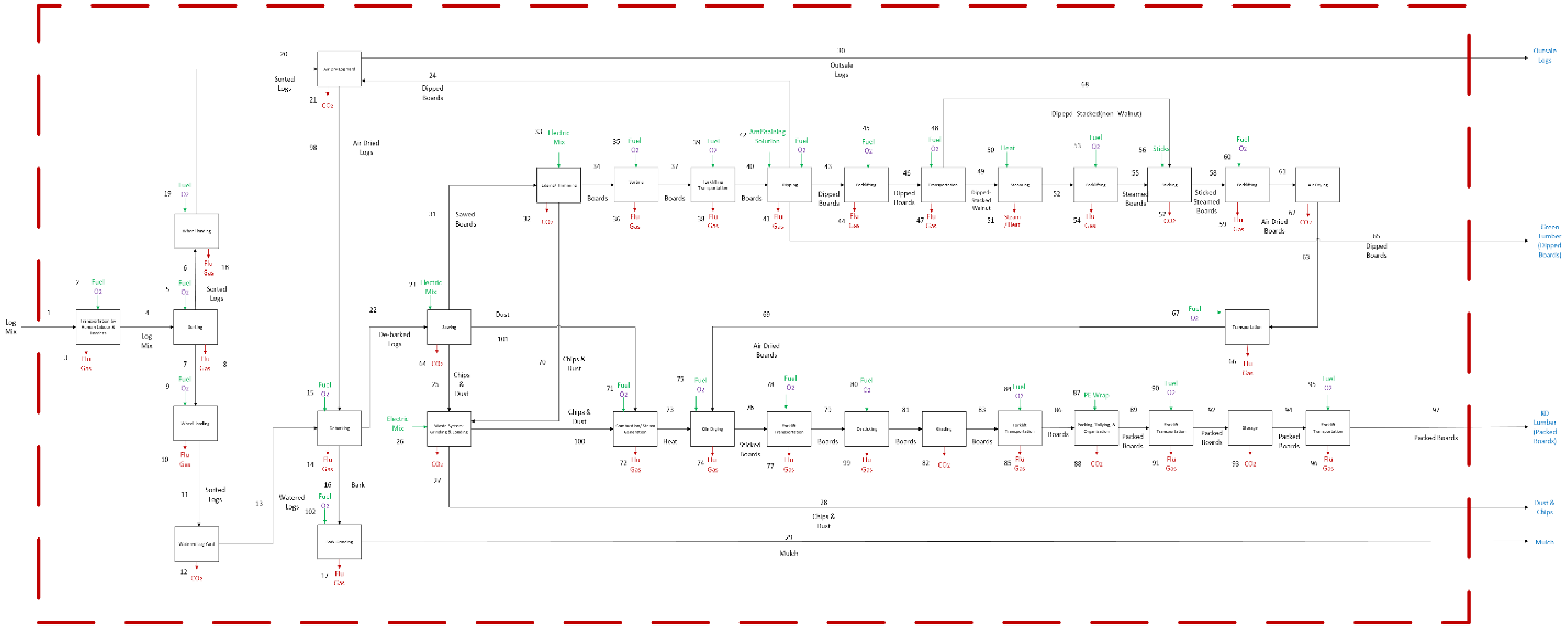

Figure 1: Process Flow Diagram of the Appalachian Hardwood Sawmill.

3.2. Goal and Scope

The goal of this LCA is to evaluate the carbon emissions associated with the production of lumber, chips and dust, mulch, and the combustion of chips and dust for hardwood lumber manufacturing. Whereas other LCA may track all Greenhouse Gas emissions (in the form of CO_2 equivalents), this assessment is solely concerned with the mass of carbon emitted. The carbon emissions are to be assessed for each step seen in the Process Flow Diagram (PFD) (Figure 1). For further information, please refer to the Goal & Scope section of this report. The functional unit of this assessment is a standardized mix of hardwood tree species in the form of dry log that is processed in the year 2024. The functional unit will be kept consistent throughout the time horizon of this analysis and serves as an average hardwood mix to realistically include all the differences in incoming material as the seasons change across the time horizon.

The time horizon for this analysis will be one calendar year. This allows the analysis to include the changing hardwood species mix that is input into the system across seasonal changes. Seasonal changes result in differing incoming log species, and the selected time horizon accounts for this variability. Yearly average carbon emissions will be determined.

3.3. Life Cycle Inventory (LCI) Analysis

The LCI Analysis involves the compilation and quantification of all relevant mass and energy flows within the system. This includes biomass (logs, boards, mulch, chips or dust), fuel (diesel or propane), water, CO_2, flu gas, heat, electricity, and certain miscellaneous items such as anti-staining solution. A mass or energy flow was determined to be relevant based on the data provided by Thomson Appalachian Hardwood, as well as its expected impact upon the production or reduction of carbon emissions. If a mass or energy flow contributed to less than 1% of total emissions, it was not considered relevant.

Initial data were gathered by personal communication with Thompson Appalachian Hardwood. A thorough examination of the production process was carried out during an onsite visit to the facility, after which production data was shared.

Data were organized in MS Excel according to the mass and energy flows labeled in the PFD (Figure 1). Each flow was based upon the functional unit: 59,800 tons dry log/year. Exact production/consumption data were only available for key steps in the process and places where streams cross the system boundary. Results were then compared to relevant literature for verification.

3.3.1. Carbon Sequestration

Carbon sequestration values were calculated using a 2023 study focused on hardwood forests in the mid-Atlantic region of the US.[16] This includes Kentucky, North Carolina, South Carolina, Tennessee, Virginia, Delaware, Maryland, New Jersey, New York, Ohio, Pennsylvania, and West Virginia. Sequestered carbon included all carbon fixed belowground over the lifespan of a stand of trees meant for harvest, for both living and dead. As such, not all sequestered carbon can be attributed to incoming logs. An even greater degree of carbon is sequestered with these inclusions. The system boundary does not include these processes and carbon sequestration was included only to better contextualize the results of the Life Cycle Impact Assessment. More information on calculations can be viewed in the Appendix.

3.3.2. Incoming Logs and Moisture Content

Given a discrepancy between the amount of incoming and outgoing dry biomass, the mass of incoming logs was increased. This was done using the excel extension Solver. Incoming logs were increased by a factor of 3.88 from 15,500 tons to 59,800 tons. More information on this assumption and the exact calculation of various streams can be seen in the Appendix (Figure A1).

Moisture content (MC) was presented using the dry basis (d.b.) method. d.b. MC is calculated as the quotient of the mass of water over the oven dry mass of wood.[17] Data on the MC of biomass throughout the process were only available immediately before and after the drying stage. The MC of all other flows were assumed based on the PFD and values from a literature review. Table 1 presents the various MC encountered throughout the process. More information on how MC was calculated, and the MC of various flows can be seen in the Appendix (Figure A2).

Table 1: Moisture content statuses of biomass at TAH.

Status	*Applies to:*	*MC (d.b.)*
Green Wood / Submerged	Incoming Logs, Watered Log Yard	130.00%
Air Dried	Yard 1	30.00%
Air Dried (Pre-Kiln)	Pre-Kiln Air Dry Yard	45.09%
Kiln Dried	Kiln	9.29%

3.4. *Life Cycle Impact Assessment (LCIA)*

The LCIA aims to calculate the magnitude and significance of global warming associated with the carbon (C) emissions produced from lumber processing at Thomson Appalachian Hardwood. Emissions resulted from four main sources: biomass combustion, biomass biodegradation, liquid fuel combustion, and electrical input from the grid. In the case of grid energy, the emissions are a function of sawmill consumption and are generated at the power plant. A 2024 provider estimate from Duck River Electric Membership Corporation of 694.48 Ib CO_2/MWh was used. For all other sources, the amount of carbon produced from complete combustion was used (Appendix A1).

A key component of an LCIA is a contribution analysis. This summarizes the largest contributors to a particular impact category, using the results of the LCI.

Table 2: Separation of emission flows into five distinct stages.

Stage	*Step*	*Flow*
Log/Board Processing	Debarking, Sawing, Edging/Trimming, Dipping, Desticking	14, 64, 32, 41, 99
Combustion & Drying	Combustion/Steam Generation, Kiln Drying	72, 74
Residue Processing	Barking Grinding, Waste System	17, 27
Transportation /Sorting	Incoming Logs, Incoming Log Sorting, Wheel Loading, Wheel Loading, Pre-Dip Sorting, Pre-Dip Transport, Post-Dip Transport, Pre-Steam Transport, Post-Steam Transport, Post-Sticking Transport, Pre-Kiln Transport, Post-Kiln Transport, Post-Grading Transport, Pre-Storage Transport, Outgoing Transport	3, 8, 10, 18, 36, 38, 44, 47, 54, 59, 66, 77, 85, 91, 96
Biodegradation	Air Dry Yard, Pre-Kiln Air Dry	21, 62

The mill process was split into five distinct phases for the contribution analysis (Table 2). Log/Board Processing includes those steps that physically alter the biomass, such as debarking, sawing, and planing. Combustion and Drying include the boiler and kilns. Residue Processing includes bark grinding and the waste system. Transportation and Sorting involve the transportation and organization of biomass throughout the system. Biodegradation includes those steps which involve long periods of prolonged storage outdoors.

3.4.1. Combustion & Drying

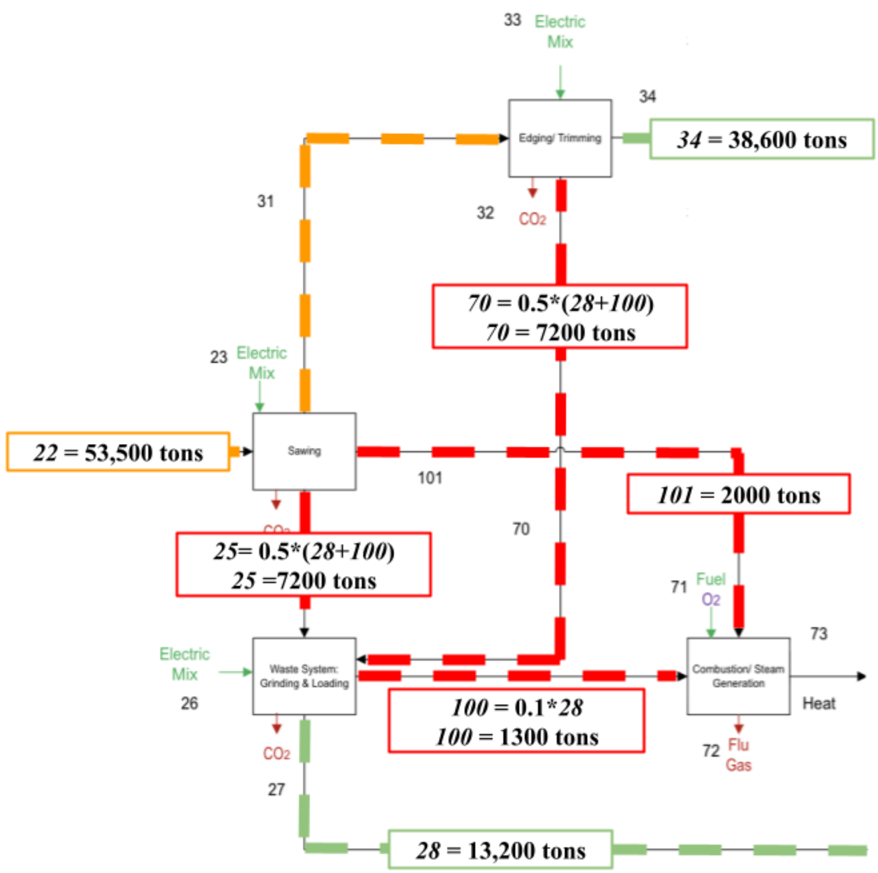

Figure 2: Combustion related flows and assumptions. Green flows are known, red assumed, and orange dependent upon assumed.

The amount of material combusted was unknown. It was assumed that 20% of the total produced chips and dust were combusted (Figure 2). This amounted to 3300 tons, the remaining 13,200 of which were sold. Further information to contextualize the results of this assumption can be found in section 4.3.2 of the Interpretation.

3.4.2. Biodegradation

Biodegradation occurs only during periods of extended storage in which certain MC conditions are met. Serious biodegradation does not occur below the fiber saturation point, or when wood is submerged.[18] The fiber saturation point is defined as the state in which the cell walls of biomass are saturated, but no free water is present. This typically occurs around 25%-35%.[19] Therefore, biodegradation was assumed to occur only when air drying, and not after, since proper air-drying results in a MC less than or equal to the fiber saturation point.[18]

$$\rho_1 = \rho_0 * e^{-kt} \quad (1)$$

Biodegradation was calculated using an exponential decay model informed by the decay rates of wood samples from two hardwood forests in eastern Illinois (Equation 1).[20] Mass loss due to biodegradation was calculated based on the difference between the final and initial specific density (ρ_1 and ρ_0) of a given wood sample. Time (t) of biodegradation was calculated based on a weighted average of the time it took (in years) common wood species between TAH and an Oklahoma State University article to air dry.[21] Decay rate (k) was calculated based on a weighted average of common tree species between TAH and the cited study.[20] For more information on these calculations see the Appendix.

3.5. Interpretation

During the interpretation phase, the results of both the LCI and LCIA are examined to formulate conclusions based upon the goal and scope. In the case of this LCA, the LCI and LCIA of Thomson Appalachian Hardwood is discussed to best identify the largest contributors to carbon emissions. Data quality is assessed using DQI's. To assist in decision making, the results of the LCI and LCIA for diesel and water use were also included. Additionally, for this same purpose, areas of improvement and high efficiency were identified. Results of the LCIA are analyzed to distinguish the exact contributors to the selected impact factor categories. Data source quality is assessed using DQI's. Results are used to support decision making.

4. Results and Discussion

4.1. LCI

4.1.1. Mass Balance

Table 3: Mass balance for the TAH sawmill.

Flow	***Flow #***	***Dry Biomass***	***Water***	***Diesel***	***Carbon***	***Propane***	***O_2***
		tons/yr	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*
Log mix in - Transport (Human Labor & Loaders)	1	59762.12	77591.16		26534.38		
Fuel + O2 in	2			57.62			200.41
Flu gas out	3		79.29		48.75		
Log mix to sorting	4	59762.12	77591.16		26534.38		
Fuel + O2 in	5			33.36			116.03
Sorting to wheel loading	6	58166.46	75519.46		25825.91		
Sorting to wheel loading	7	1595.66	2071.70		708.47		
Flu gas out	8		45.90		28.22		
Fuel + O2 in	9			32.46			112.89
Flu gas out	10		44.66		27.46		
Sorted logs to watered log yard	11	1595.66	2071.70		708.47		
CO2 out	12						
Watered logs to debarking	13	1595.66	2071.70		708.47		
Flu gas out	14		49.74		30.58		
Fuel + O2 in	15			36.15			125.72
Bark to bark grinding	16	6597.43	2155.09		2929.26		
Flu gas out	17		7.90		4.85		
Flu gas out	18		71.06		43.69		
Fuel + O2 in	19			51.64			179.60
Sorted logs to air dry yard	20	58166.46	75519.46		25825.91		

Flow	***Flow #***	***Dry Biomass***	***Water***	***Diesel***	***Carbon***	***Propane***	***O_2***
		tons/yr	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*
CO2 out	21				94.61		
Debarked Logs to Sawing	22	52960.36	17299.80		23514.40		
Dipped boards from dipping to air dry yard	24	2487.79	746.34		1104.58		
Chips & dust	25	7236.89	2363.97		1104.58		
CO2 out	27				0.49		
Chips & dust from waste system out for sale	28	13157.99	4298.13		5842.15		
Mulch from bark grinding for sale	29	6597.43	2155.09		2929.26		
Outsale logs from air dry log yard	30	2479.05	743.71		1100.70		
Sawed boards to edging trimming	31	29823.80	9742.11		13241.77		
CO2 out	32			0.48	116.28		
Boards to sorting	34	36512.87	11927.14		16211.72		
Fuel + O2 in	35			5.74			19.96
Flu gas out	36		7.90		4.85		
Boards to forklifting	37	36512.87	11927.14		16211.72		
Flu gas out	38		2.03		1.25		
Fuel + O2 in	39			1.48			5.13
Boards to dipping	40	36512.87	11927.14		16211.72		16211.72
Flu gas out	41		7.90		4.85		
Antistaining solution in + fuel + O2	42			5.74			19.96
Dipped boards to forklifting	43	25479.72	9702.56		11312.99		

Flow	*Flow #*	*Dry Biomass*	*Water*	*Diesel*	*Carbon*	*Propane*	*O_2*
		tons/yr	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*
Flu gas out	44		2.03		1.25		
Fuel + O2 in	45			1.48			5.13
Dipped boards to transportation	46	25479.72	9702.56		11312.99		
Flu gas out	47		2.03		1.25		
Fuel + O2 in	48			1.48			5.13
Dipped-stacked walnut boards to steaming	49	791.11	237.33		351.25		
Steamed boards to forklift	52	791.11	237.33		351.25		
Fuel + O2 in	53			1.48			5.13
Flu gas out	54		2.03		1.25		
Steamed boards to sticking	55	791.11	237.33		351.25		
CO2 out	57						
Sticked-steamed boards to transport	58	25479.72	9702.56		11312.99		
Flu gas out	59		2.03		1.25		
Fuel + O2 in	60			1.48			5.13
Sticked-steamed boards to air drying	61	25479.72	9702.56		11312.99		
CO2 out	62				39.74		
Air dried boards to transportation	63	25390.21	11448.44		11273.25		
CO2 out	64				0.49		
Green lumber (dipped boards) out for sale	65	8545.37	2563.61		3794.14		
Flu gas out	66		2.03		1.25		

Flow	*Flow #*	***Dry Biomass*** *tons/yr*	***Water*** *tons/yr*	***Diesel*** *tons/yr*	***Carbon*** *tons/yr*	***Propane*** *tons/yr*	***O_2*** *tons/yr*
Fuel + O2 in	67			1.48			5.13
dipped-stacked non walnut to sticking	68	24688.61	9465.23		10961.74		
Air dried boards from transportation after drying to kiln drying	69	25390.21	11448.44		11273.25		
Bark from edging/ trimming to chipping	70	7236.89					
Fuel + O2 in	71			5.74			19.96
Flu gas out	72		7.90		1465.39		
Flu gas out + CO2	74		2.03		72.96		
Fuel + O2 in	75			1.48		87.76	
Sticked boards from kiln drying to forklift	76	25390.21	2358.75		11273.25		
Flu gas out	77		7.90		4.85		
Fuel + O2 in	78			5.74			19.96
Sticked boards from forklift to desticking	79	25390.21	2358.75		11273.25		
Fuel + O2 in	80			5.74			19.96
Boards to grading	81	25390.21	2358.75		11273.25		
CO2 out	82						
Boards to forklift transport	83	25390.21	2358.75		11273.25		
Fuel + O2 in	84			5.74			19.96
Flu gas out	85		7.90		4.85		
Boards to packing/tallying/organization	86	25390.21	2358.75		11273.25		
CO2 out	88						
Packed boards	89	25390.21	2358.75		11273.25		

Flow	***Flow #***	***Dry Biomass***	***Water***	***Diesel***	***Carbon***	***Propane***	***O_2***
		tons/yr	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*	*tons/yr*
Fuel + O2 in	90			5.74			19.96
Flu gas out	91		7.90		4.85		
Packed boards to storage	92	25390.21	2358.75		11273.25		
CO2 out	93						
Packed boards to forklifting	94	25390.21	2358.75		11273.25		
Fuel + O2 in	95			5.74			19.96
Flu gas out	96		7.90		4.85		
KD lumber (packed boards) out for sale	97	25390.21	2358.75		11273.25		
Air dried logs to debarking	98	57962.13	17388.64		25735.18		
Flu gas out	99		7.90		4.85		
Chips & Dust from waste to combustion	100	1315.80	429.81		584.21		
Dust from sawing to combustion	101	1973.70	644.72		876.32		
Fuel + O2 in	102			5.74			19.96

4.1.2. Energy Balance

Table 4: Energy Balance for the TAH sawmill. Only those flows with energy were included. Energy from a given fuel is listed in the same flow as the fuel itself, except in the case of biomass combustion. The energy resulting from the combustion of flows 101 and 102 is listed in flow 73 as heat, after loss due to boiler inefficiency is subtracted.

Flow	***Flow #***	***Diesel***	***Electric mix***	***Heat***	***Propane***
		1000 kWh/yr	*1000 kWh/yr*	*1000 kWh/yr*	*1000 kWh/yr*
Fuel + O2 in	2	624.40			
Flu gas out	3			643.21	
Fuel + O2 in	5	361.49			
Flu gas out	8			372.38	
Fuel + O2 in	9	351.72			
Flu gas out	10			362.32	
Flu gas out	14			403.49	
Fuel + O2 in	15	391.69			
Flu gas out	17			64.05	
Flu gas out	18			576.42	
Fuel + O2 in	19	559.56			
Electric mix in	23		4.39		
Electrix mix in	26		4.39		
Electric mix in	33		1051.87		
Fuel + O2 in	35	62.17			
Flu gas out	36			64.05	
Flu gas out	38			16.47	
Fuel + O2 in	39	15.99			
Flu gas out	41			64.05	
Antistaining solution in + fuel + O2	42	62.17			

Flow	***Flow #***	***Diesel*** *1000 kWh/yr*	***Electric mix*** *1000 kWh/yr*	***Heat*** *1000 kWh/yr*	***Propane*** *1000 kWh/yr*
Flu gas out	44			16.47	
Fuel + O2 in	45	15.99			
Flu gas out	47			16.47	
Fuel + O2 in	48	15.99			
Heat in	50				
Steam/heat out	51				
Fuel + O2 in	53	15.99			
Flu gas out	54			16.47	
Flu gas out	59			16.47	
Fuel + O2 in	60	15.99			
Flu gas out	66			16.47	
Fuel + O2 in	67	15.99			
Fuel + O2 in	71	62.17			
Flu gas out	72			64.05	
Heat to kiln drying	73			13440.45	
Flu gas out + CO2	74			16.47	
Fuel + O2 in	75	15.99			1025.03
Flu gas out	77			64.05	
Fuel + O2 in	78	62.17			
Fuel + O2 in	80	62.17			
Fuel + O2 in	84	62.17			
Flu gas out	85			64.05	
Fuel + O2 in	90	62.17			
Flu gas out	91			64.05	
Fuel + O2 in	95	62.17			
Flu gas out	96			64.05	

Flow	*Flow #*	*Diesel*	*Electric mix*	*Heat*	*Propane*
		1000 kWh/yr	*1000 kWh/yr*	*1000 kWh/yr*	*1000 kWh/yr*
Flu gas out	99			64.05	
Fuel + O2 in	102	62.17			

4.1.3. Energy Consumption Analysis

Table 5: Annual energy consumption for the TAH sawmill. If a fuel, mass is included.

Flow	***Flow #***	***Diesel***		***Biomass***		***Propane***		***Electric mix***
		tons/yr	*1000 kWh/yr*	*tons/yr*	*1000 kWh/yr*	*tons/yr*	*1000 kWh/yr*	*1000 kWh/yr*
Fuel + O2 in	2	57.63	624.40					
Fuel + O2 in	5	33.37	361.49					
Fuel + O2 in	9	32.46	351.72					
Fuel + O2 in	15	36.15	391.69					
Fuel + O2 in	19	51.65	559.56					
Electric mix in	23							4.39
Electrix mix in	26							4.39
Electric mix in	33							1051.87
Fuel + O2 in	35	5.74	62.17					
Fuel + O2 in	39	1.48	15.99					
Antistaining solution in + fuel + O2	42	5.74	62.17					
Fuel + O2 in	45	1.48	15.99					
Fuel + O2 in	48	1.48	15.99					
Heat in	50							
Steam/heat out	51							
Fuel + O2 in	53	1.48	15.99					
Fuel + O2 in	60	1.48	15.99					
Fuel + O2 in	67	1.48	15.99					
Fuel + O2 in	71	5.74	62.17					
Heat to kiln drying	73			3290.11	13440.45			

Flow	Flow #	Diesel		Biomass		Propane		Electric mix
		tons/yr	*1000 kWh/yr*	*tons/yr*	*1000 kWh/yr*	*tons/yr*	*1000 kWh/yr*	*1000 kWh/yr*
Fuel + O2 in	75	1.48	15.99			87.77	1025.03	
Fuel + O2 in	78	5.74	62.17					
Fuel + O2 in	80	5.74	62.17					
Fuel + O2 in	84	5.74	62.17					
Fuel + O2 in	90	5.74	62.17					
Fuel + O2 in	95	5.74	62.17					
Fuel + O2 in	102	5.74	62.17					
Total:		273.25	2960.33	3290.11	13440.45	87.77	1025.03	1060.64

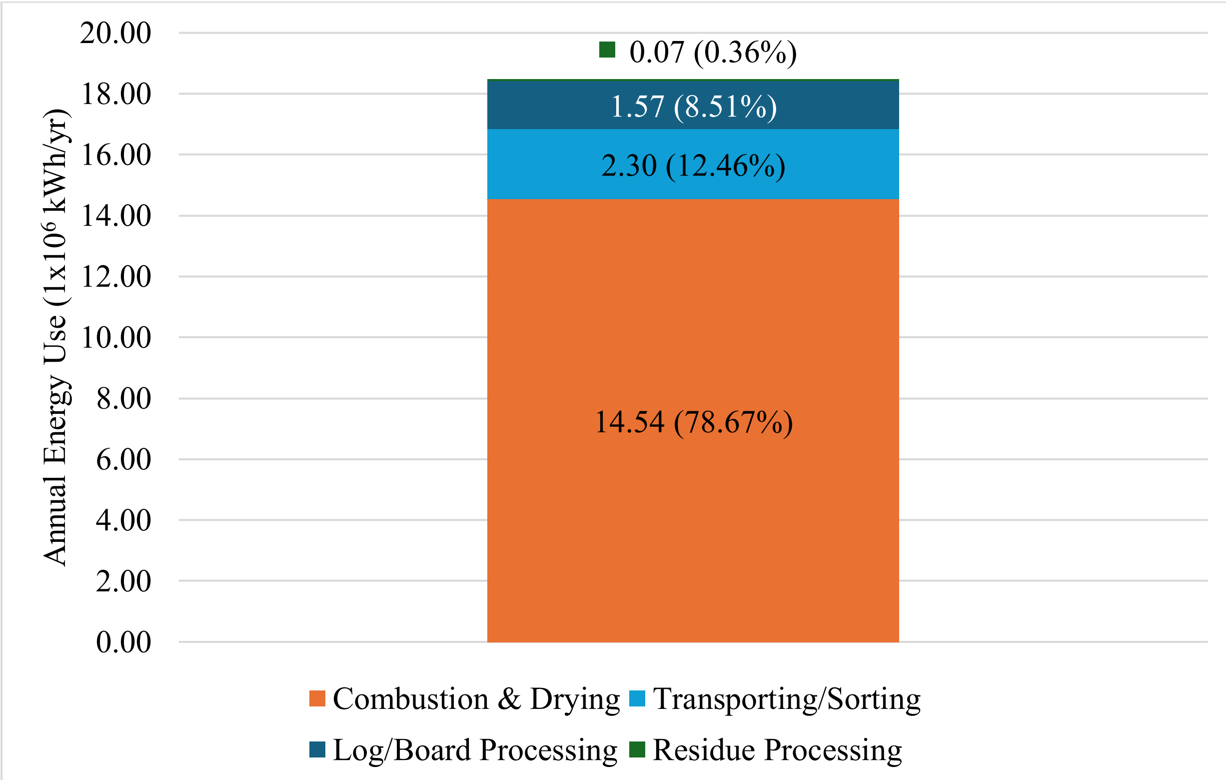

Figure 3: Contribution analysis for annual energy consumption of the TAH sawmill.

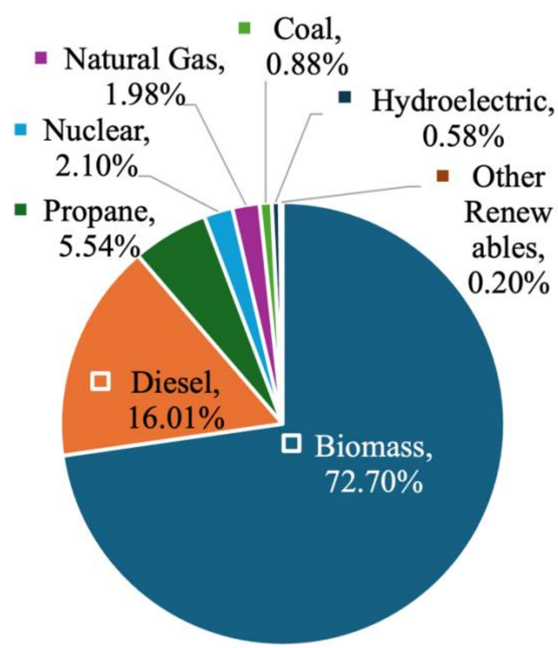

Figure 4: Composition of annual energy use for the TAH sawmill.

Annual energy use (including electric and fuel combustion) was calculated to be 18.49×10^6 kWh. The combustion and drying stage had the largest demand and totaled 14.54×10^6 kWh, or 78.67% of total demand. Transportation and sorting used solely diesel fuel and made up 12.46% of total demand. Log and board processing made up 8.51% of total demand and residue processing the remaining 0.36% (Figure 3).

Heat produced from biomass provides 72.70% of the energy used in the sawmill. Fossil-fuel energy sources composed 24.41% of annual energy use. About 73.49% of total use is composed of renewable sources (Figure 4). The appendix depicts information on the local energy grid mix, as well as energy loss during drying (Table A10, Figure A3).

4.2. LCIA

4.2.1. Carbon Emissions

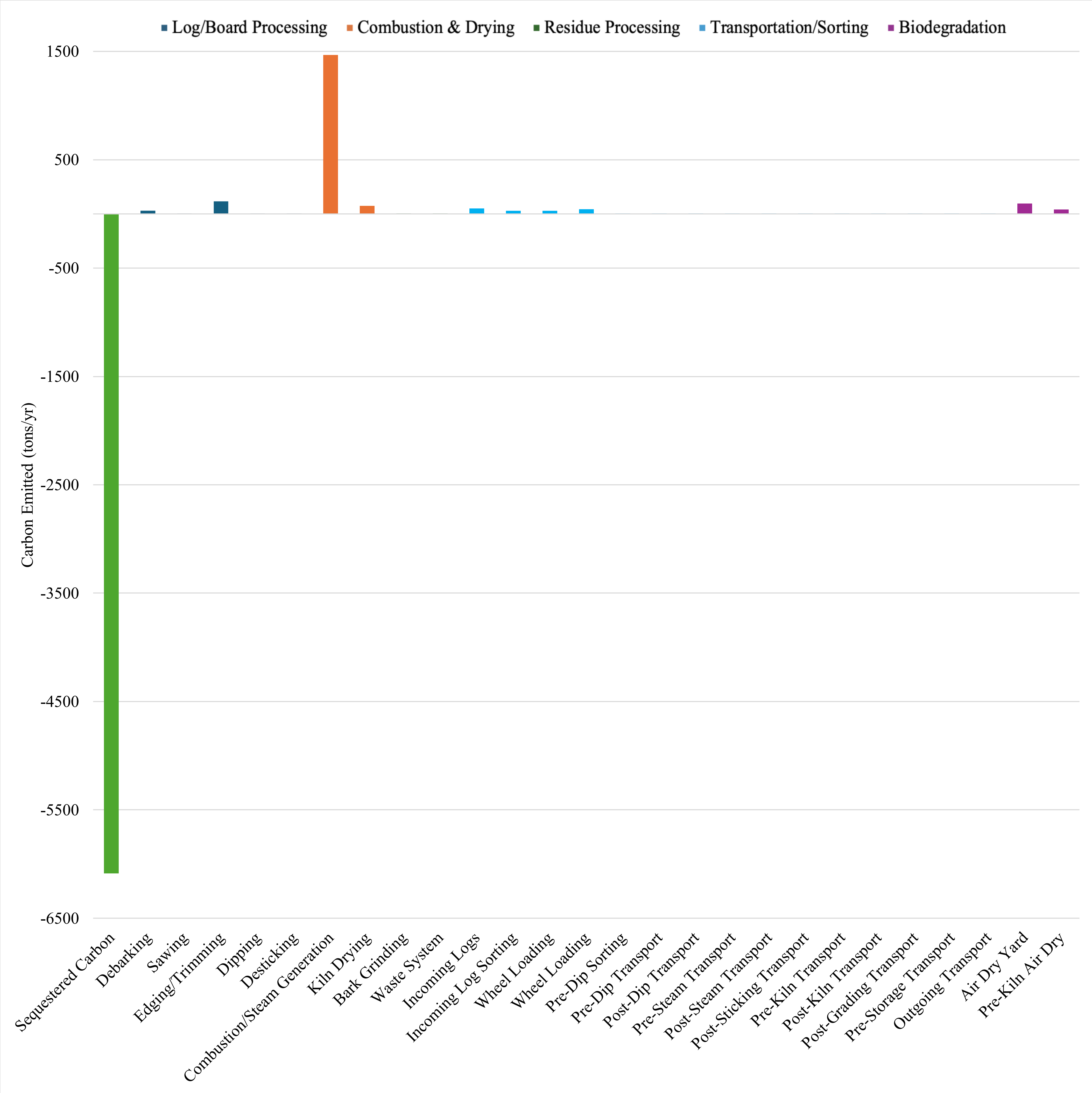

Figure 5: Annual carbon emissions associated with each step of the process for the TAH sawmill. Steps colored according to stage.

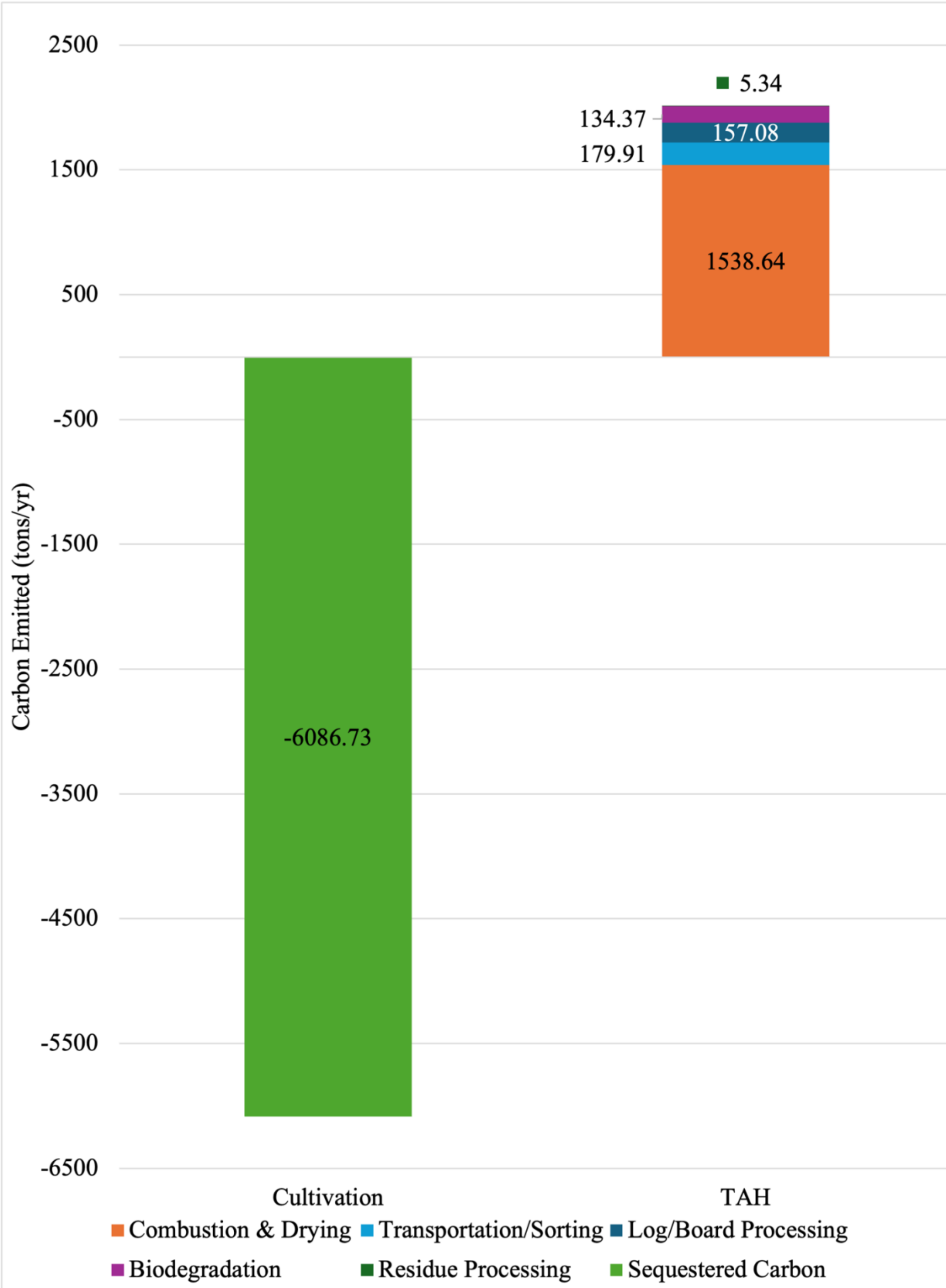

Figure 6: Contribution Analysis of Annual Carbon Emissions for the TAH Sawmill.

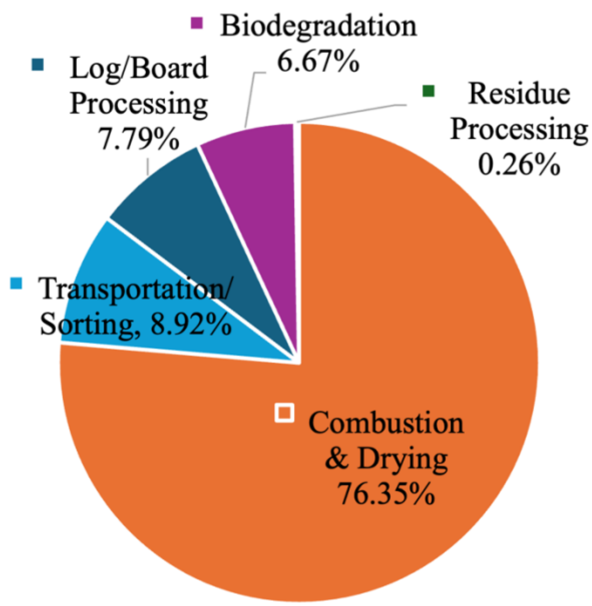

Figure 7: Composition of Annual Carbon Emissions for the TAH Sawmill

The annual emissions determined for the TAH sawmill totaled to 2015.34 tons of carbon. Combustion and drying was the highest contributor, producing 1538.64 tons of carbon annually (Figure 6). The next highest contributor was transportation and sorting, followed by log and board processing, biodegradation and then residue processing (Figure 7).

4.2.2. Log/Board Processing

Log and board processing was estimated to emit 157.08 tons of carbon a year, or 7.79% of total emissions. Log and board processing included debarking, sawing, edging and trimming, dipping (for walnut only), and desticking and planing (Figure 5). A mix of diesel, electricity, and biomass provided energy for this stage of the process (A6).

4.2.3. Combustion and Drying

The combustion and drying stage included all emissions produced from the boiler and drying kilns. The stage was estimated to emit 1538.64 tons of carbon annually, making up 76.35% of total emissions. Drying wood is an energy-intensive process that requires space to be maintained at a high temperature for extended periods. The facility used seven kilns for drying, their energy supplied by propane and a wood-fired boiler and steam coil system, respectively.

Based on the assumed amount of biomass combusted, 92.41% of the energy for drying comes from biomass and 7.05% from propane. The remaining 0.54% comes from diesel that is used to operate forklifts used for loading and unloading lumber into the kilns. (Table A6). This involves the combustion of 3290.11 tons of biomass and 87.77 tons of propane (Table 5). The combustion-related assumptions are presented in the Appendix (Figure A1).

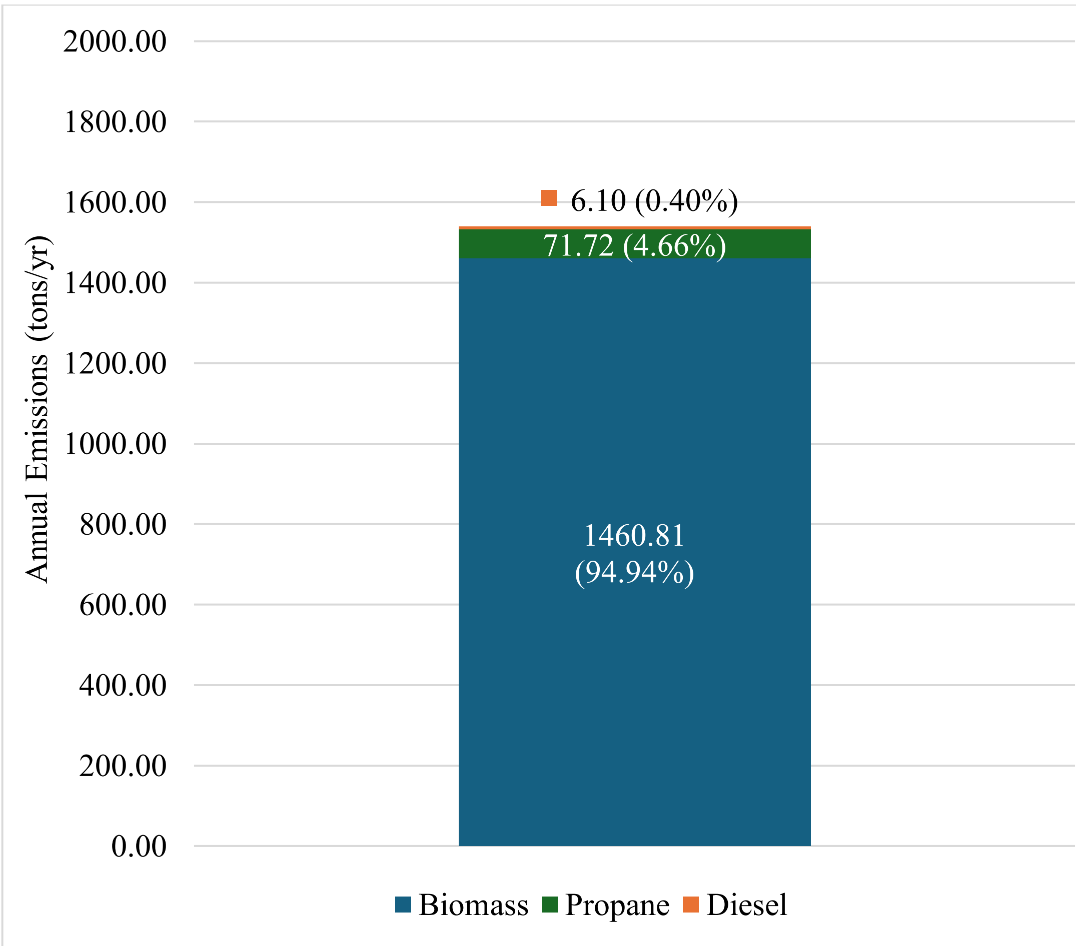

Figure 8: Contribution analysis of annual carbon emissions for the combustion and drying stage.

Of the 1538.64 tons of carbon produced from the combustion and drying stage, 94.94% came from the combustion of biomass. 4.66% resulted from the combustion of propane and 0.40% from the combustion of diesel (Figure 8).

4.2.4. Residue Processing

Emissions resulting from residue processing were negligible, totalling to 5.34 tons of carbon a year. This stage included bark grinding and the waste system (Figure 5).

4.2.5. Transportation/Sorting

Transportation and sorting was estimated to emit 179.91 tons of carbon a year, or 8.93% of total emissions. This energy was provided entirely by diesel and entailed the operation of heavy machinery (Table A6).

4.2.6. Biodegradation

Emissions due to biodegradation of biomass during air drying were estimated to be 134.37 tons of carbon, or 6.67% of total annual emissions (Figure 5). This affected flows 30, 63, and 98 (Figure 1).

4.3. Interpretation

4.3.1. Sensitivity Analysis

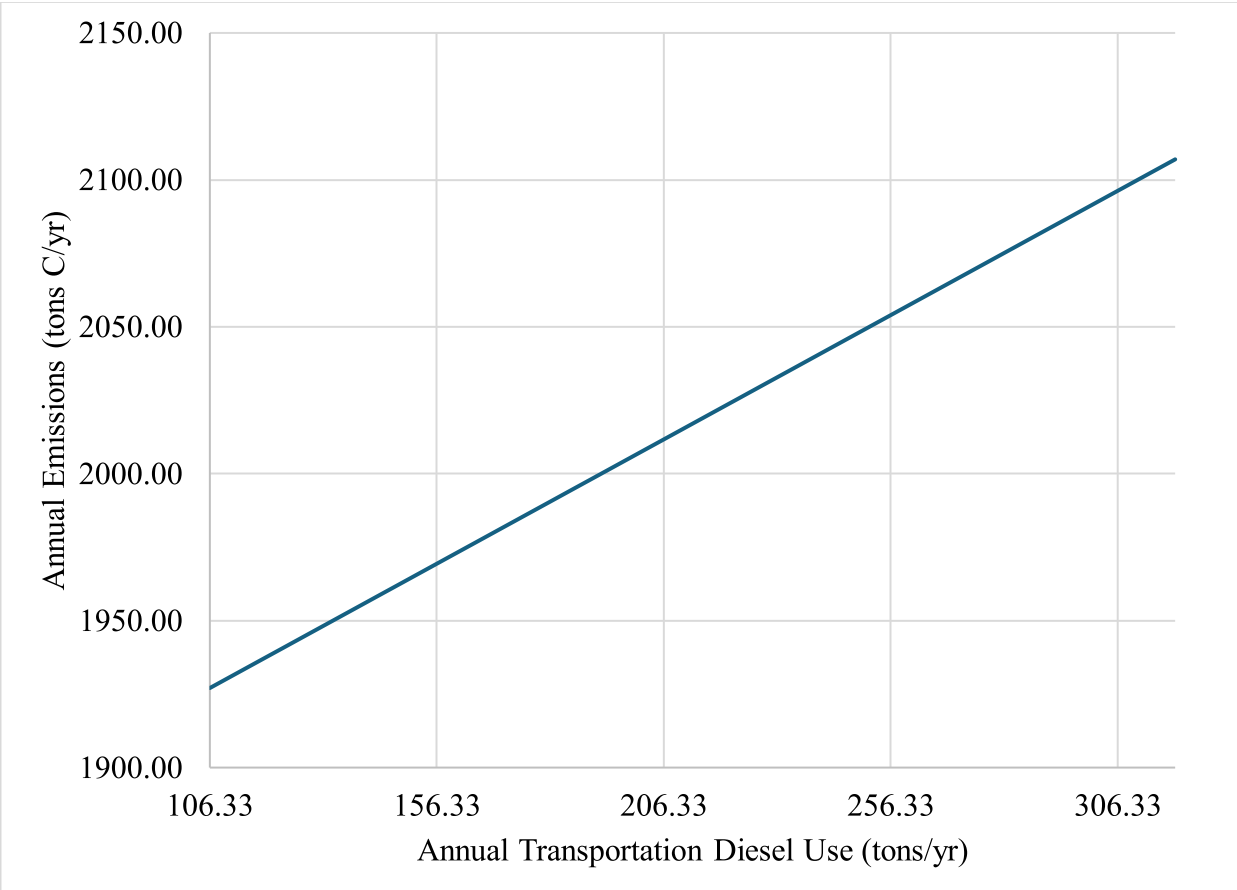

Figure 9: Sensitivity analysis for annual diesel use, in terms of tons of carbon. Only diesel used in the transportation/sorting stage was varied.

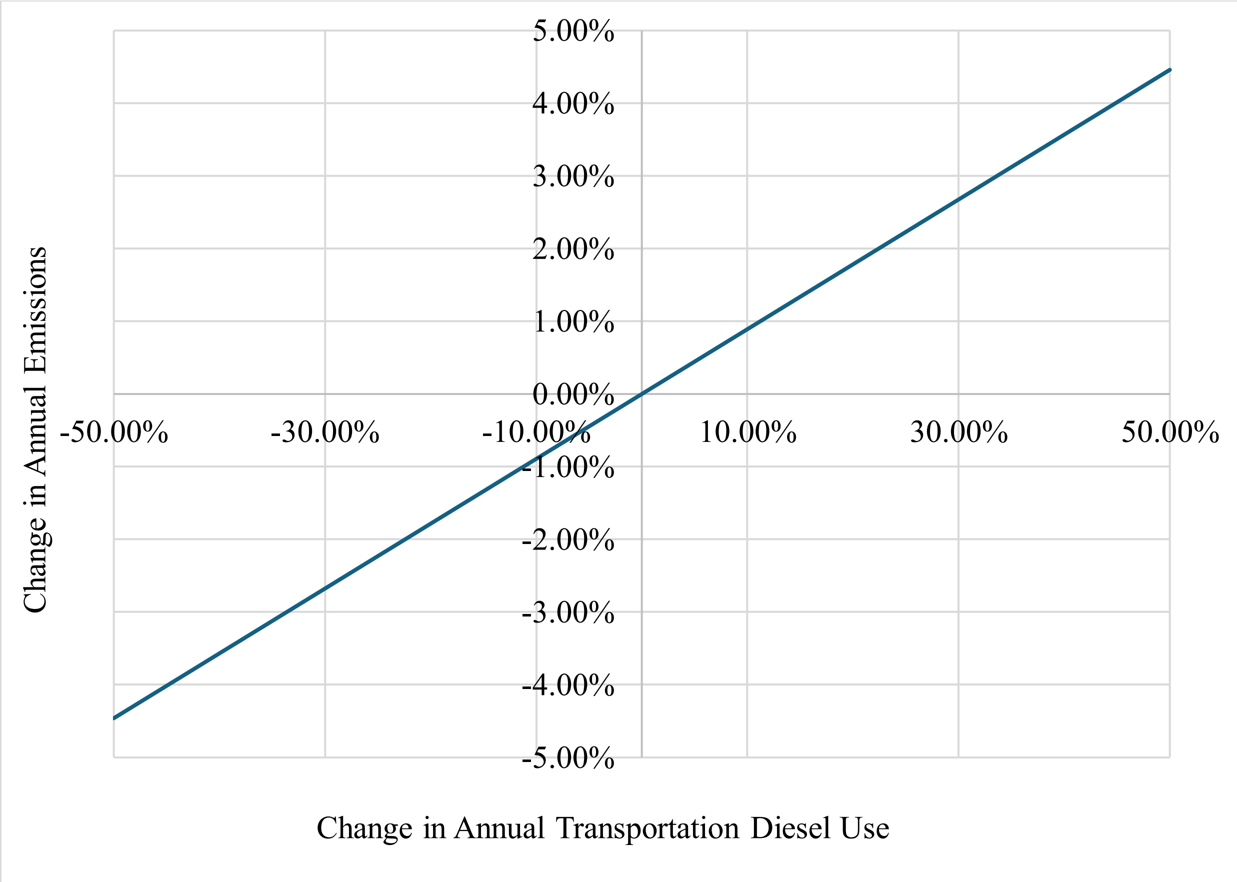

Figure 10: Sensitivity analysis for annual diesel use, in terms of % change of variables. Only diesel used in the transportation/sorting stage was varied.

Diesel was a required input in 21 out of 102 steps of the process, 15 of which entailed transport or sorting. This amounted to 212.66 tons. This mass was varied by ±50%, resulting in a distribution between 106.33 and 318.99 tons. This sensitivity analysis models the potential effect that spatial consolidation might have upon emissions. If the distance between steps is reduced, diesel use and resulting emissions will decrease.

Total emissions in both scenarios varied by ±89.96 tons of carbon, since transport-related energy demand for each was assumed to be the same (Figure 9). This resulted in a difference in annual emissions of ±4.46% (Figure 10). The relationship between diesel uses and annual emissions was linear, meaning that each change in results causes a proportionate change in emissions.

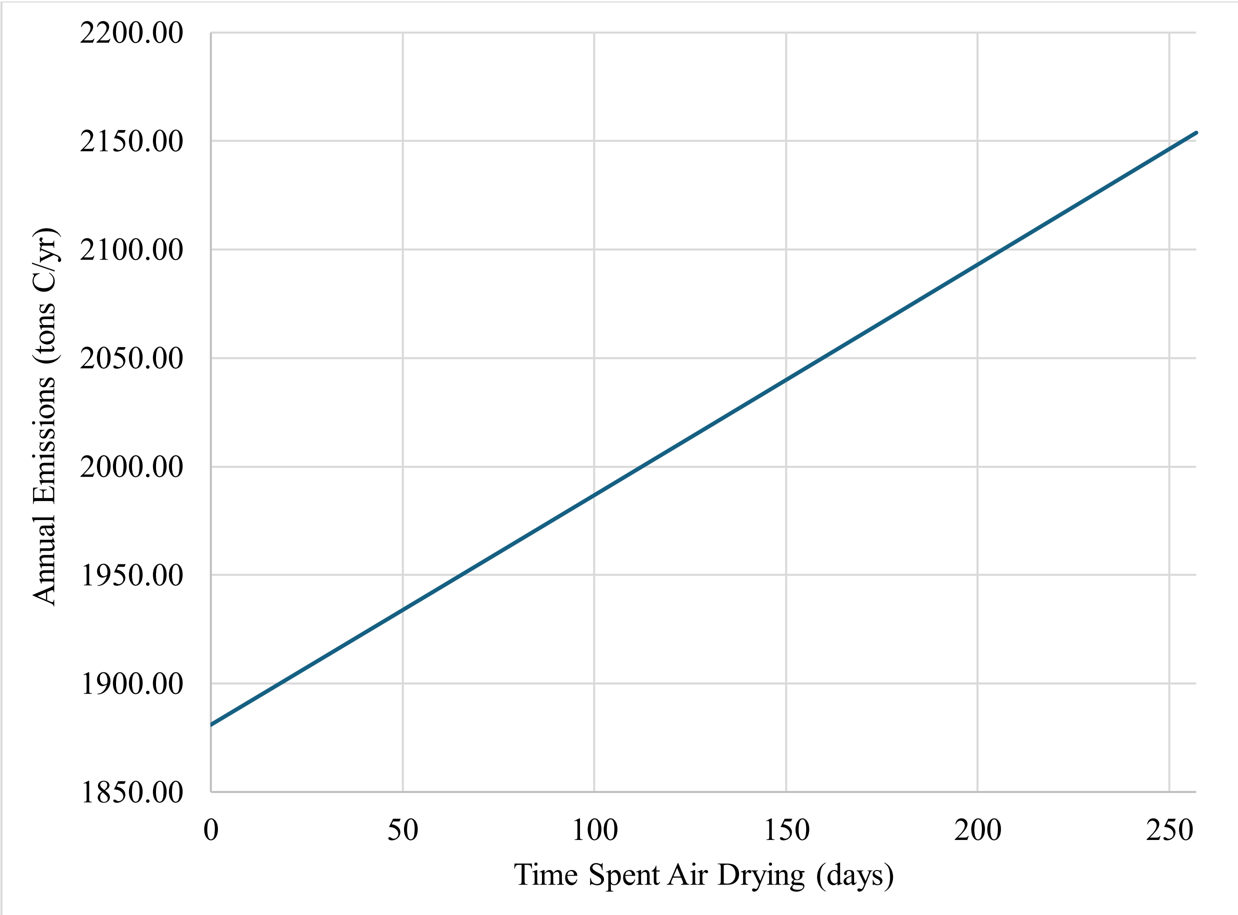

Figure 11: Sensitivity analysis for time spent air drying, in terms of variance from the baseline of 129 days. See Figure 3 for those steps included.

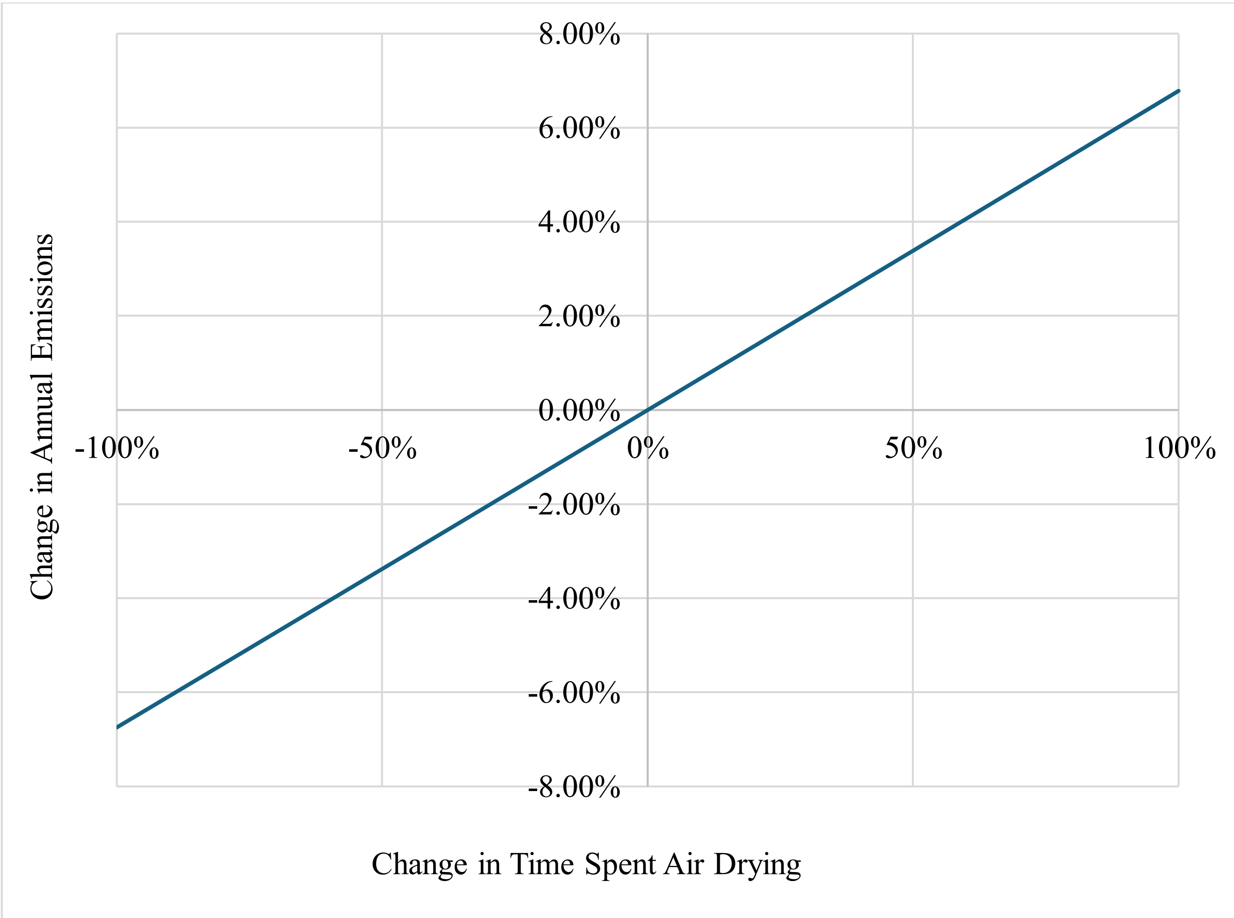

Figure 12: Sensitivity analysis for time spent air drying, in terms of % change from the baseline of 129 days. See Figure 3 for steps included.

Biodegradation occurred in three steps of the process. In each case, biomass was assumed to dry outdoors for 129 days. This analysis varied that amount by ±100%, resulting in a distribution between 0 and 257 days. This displays a conservative estimate of how significant an effect the length of time spent drying outdoors has upon annual emissions.

Variation of the time spent drying resulted in a change in annual emissions by -136.06 and +136.68-tons C (Figure 11). This corresponds to a change in total emissions by -6.75% and +6.78% (Figure 12). This discrepancy is a product of the exponential decay model used for biodegradation. The more days spent outdoors, the greater the corresponding increase in emissions.

4.3.2. Energy Consumption Analysis

The annual energy demand of the sawmill totaled to 18.49×10^6 kWh. Combustion and drying composed 78.67% of demand (Figure 2). This is higher than the expected 60-70% that drying in hardwood sawmills averaged between 2000-2010.[22,23] 92.41% of the drying demand was supplied by the combustion of 3290.11 tons of biomass and 7.05% by the combustion of 87.77 tons of propane. The remaining 0.54% came from diesel and entailed loading and unloading of the boiler and kilns (Table 5, Table A6, Table A7). The fuel mass requirement for combustion is a product of the lesser lower heating value (LHV) of biomass. Whereas propane has a LHV of 46.35 MJ/kg, the LHV of biomass was calculated to be 16.38 MJ/kg.

Fossil fuel-based energy input was 24.41% of total energy input, which is lower than the average 26.69% for a hardwood sawmill located in the US Northeast and North Central.[11] Biomass combustion supplied 72.70% of total energy demand. In comparison, a survey of Oregon sawmills revealed that, of those which utilized wood residue for energy, biomass made up 69.7% of total energy use.[24]

4.3.3. Carbon Emissions

The sawmill produces an estimated 2015.34 tons of carbon a year, based on an input of 59,762.12 dry tons of green hardwood log. This translates to 67.45 Ib carbon/ton hardwood log. A 2020 study by the Consortium for Research on Renewable Industrial Materials (CORRIM) found that Northeastern and North Central US hardwood sawmills emit an average of 366.67 Ib CO_2eq during processing for every 1 m^3 (423.8 BF) of planed dry lumber produced.[11] Another study taking place in New Brunswick, Canada found that hardwood sawmills emitted 89.68 Ib CO_2eq per 1 m^3 (423.8 BF) of rough green lumber.[12]

Of the 1538.64 tons of carbon produced from combustion and drying stage, 94.04% came from the combustion of 3290.11 tons of biomass. An additional 4.66% came from the combustion of 87.77 tons of propane. Including diesel, combustion and drying stage produces 77.82 tons of carbon produced by fossil fuels.

It is important to note how the assumptions made over the course of this study may have affected its results. To maintain the mass balance of biomass, the mass of incoming green hardwood log was increased by a factor of 3.85. Although fuel and electrical inputs remained the same, emissions resulting from biodegradation rose significantly in the early steps of the process (Figure 4). This could explain why biodegradation contributed to over 28.27% of total emissions.

Moisture content was calculated based on an incoming average of species when green (Table 16). To ensure greater accuracy, moisture content should be measured across a sample of logs and boards. Wood is a hygroscopic material, meaning moisture content has a significant effect upon its mass and volume. Therefore, it is important to specify the moisture content when working with wood. Wood being processed can exist in multiple different states: saturated, air dried, oven dried, or green.[25] Water content should be measured at each state for accuracy.

As of 2024, the grid energy mix that TAH relies on produces on average 315.010829 kg CO_2/MWh (694.48 Ibs CO_2/MWh). In 2023 TAH sold 9500 tons of mulch, 18,400 tons of chips, and 9400 tons of dust. More of this biomass can be rerouted to combustion and used for clean energy production with the conversion of more biomass powered boilers. The efficiency of kilns themselves can be improved according to the suggestions compiled by a 2000 paper on drying hardwood lumber. These include (but are not limited to): use of heat exchangers on vents to recycle heat, accurate moisture content measurement, and decrease of fan speeds.[26] As both the CORRIM and New Brunswick assessments reported, with the replacement of manual sawing with computer-assisted sawing, overall waste and error would decrease. This could lead to a potential reduction in emissions.

4.3.4. Carbon sequestration

Please refer to the Appendix for details of calculated carbon sequestration.

4.3.5. Consistency and Completeness

Completeness check consists of all relevant mass, energy, and emission flows of both scenarios. Data provided by Thomson Appalachian Hardwood indicates that incoming and outgoing material flows are complete and accurate. Minor and negligible flows such as lubricants and saw blade replacements were excluded from analysis. Boiler combustion was calculated based on the assumed amount of biomass which enters the kiln (Figure A1). This totaled 20% of the chips and dust generated by sawing and the waste system. Resulting emissions were calculated assuming complete combustion (Equation 3). To calculate resulting energy, the HHV of the biomass was calculated using the Guar and Reede approximation (Equation 7). LHV was determined from this (Equation 8). Factoring in the amount of biomass combusted, its LHV, and the efficiency of the boiler, resulting energy in the form of heat was calculated (Equation 9). In this case, the designated system boundary includes significant flows with minimal gaps in data, ensuring the capture of all significant flows.

Consistency is verified by ensuring all assumptions in methodology are equally applied across the system boundary for both scenarios. The input data matches the flows included in the system's boundary. The data was normalized to reflect a functional unit of yearly production of kiln dried lumber output. All values came from 2023-2024 data. Assumptions and data are consistent within the inventory analysis with no noted deviations.

In addition to completeness and consistency, Data Quality Indicator (DQI) scores were assigned to the data sources used to determine each numbered flow. Data that were provided from TAH were given highest scores due to its relevancy and accuracy. All scores were in the range of 4 to 5 (Table 4.).

Table 4: Data Quality Indicator (DQI) scores calculated for each flow of the system. Values 1-5 which indicates worst to best.

Process	Tech Rep.	Geo Rep.	Time Rep.	Reliability	Overall DQI
Log mix in - Transport	5	5	5	5	5
Fuel + O2 in	4	5	5	5	4.75
Flu gas out	4	5	5	5	4.75
log mix to sorting	5	5	5	5	5
Fuel + O2 in	4	5	5	5	4.75
sorting to wheel loading	5	5	5	5	5
sorting to wheel loading	5	5	5	5	5
flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
sorted logs to watered log yard	5	5	5	5	5
CO2 out	4	5	5	5	4.75
Watered logs to debarking	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
bark to bark grinding	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
sorted logs to air dry yard	5	5	5	5	5
CO2 out	4	5	5	5	4.75
air dried logs to debarking	5	5	5	5	5
Airdried logs to kiln drying	5	5	5	5	5

dipped boards from dipping to air dry yard	5	5	5	5	5
Air Dried Boards dipped boards to sale	5	5	5	5	5
Bark from bark grinding to sale	5	5	5	5	5
Debarked Logs to Sawing	4	5	5	5	4.75
electric mix in	5	5	5	5	5
CO2 out	4	5	5	5	4.75
dust from sawing to blowing	4	5	5	5	4.75
electric mix in	5	5	5	5	5
CO2 out	4	5	5	5	4.75
dust out for sale	5	5	5	5	5
bark from edging/ trimming to chipping	5	5	5	5	5
Fuel + O2 in	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
dust from chipping to combustion	5	5	5	5	5
Flu gas	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
dust from sawing to combustion	5	5	5	5	5
heat to kiln drying	5	5	5	5	5
CO2 out	4	5	5	5	4.75
sticked boards from kiln drying to desticking	5	5	5	5	5
CO2 out	4	5	5	5	4.75
boards to forklift transport	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
boards to grading	5	5	5	5	5
CO2 out	4	5	5	5	4.75
boards to forklift transport	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
boards to packing/ tallying/ organization	5	5	5	5	5
CO2 out	4	5	5	5	4.75
PE wrap in	3	3	3	3	3
packed boards	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5

packed boards to storage	5	5	5	5	5
CO2 out	4	5	5	5	4.75
packed boards to forkliftinf	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
packed boards out for sale	5	5	5	5	5
dipped boards out for sale	4	5	5	5	4.75
sawed boards to edging trimming	5	5	5	5	5
CO2 out	4	5	5	5	4.75
electric mix in	5	5	5	5	5
boards to sorting	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
boards to forklifting	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
boards to dipping	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
antistaining solution in	3	4	4	4	3.75
dipped boards to forklifting	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
dipped boards to stacking	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
dipped-stacked boards to steaming	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
Fuel + O2 in	5	5	5	5	5
dipped-stacked walnut boards to steaming	5	5	5	5	5
dipped-stacked non walnut to sticking	5	5	5	5	5
steam/heat out	4	5	5	5	4.75
heat in	4	5	5	5	4.75
steamed boards to sticking	5	5	5	5	5
CO2 out	4	5	5	5	4.75
sticks in	3	4	4	4	3.75
sticked-steamed boards to airdrying	4	5	5	5	4.75
co2 out	4	5	5	5	4.75
air dried boards to transportation	5	5	5	5	5

steamed boards from steaming for sale	5	5	5	5	5
dipped boards from forklifting to transportation	5	5	5	5	5
Fuel + O2 in	5	5	5	5	5
Flu gas out	4	5	5	5	4.75
dipped boards from transportation to kiln drying	5	5	5	5	5
steamed boards from transportation to kiln drying	5	5	5	5	5
air dried boards from transportation after drying to kiln drying	5	5	5	5	5
Flu gas out	4	5	5	5	4.75

5. Conclusions

The goal of this study was to assess the annual carbon emissions associated with the operation of the Thomson Appalachian Hardwood sawmill. Unlike other LCA studies about hardwood processing, the geographic and temporal scopes are not specific to the South. This allows results to capture greater specificity for the region, which includes the species most often processed in the southeastern region of the USA. Since this analysis was gate-to-gate and site-specific, it allowed specificity on the intricacies of the sawmilling processes (Figure 1). Product sale and end of use were not included in this analysis. This was done to better compare results with other LCA studies on the subject of sawmill processing and was outside the scope of this work.

Drying was the predominant contributor to carbon emissions, and this is mirrored in published literature on sawmill LCAs. Using biomass powered boilers to heat kilns is overall a carbon-neutral process. Provided timberlands are consistently cultivated; burning biomass for boiler run kiln dryers does not increase atmospheric carbon.[27] A study of a larger scope that includes lumber cultivation is recommended to provide further evidence of the carbon neutrality of biomass boiler powered kilns.[28]

Reported sawmill production vary widely depending on region and scope (1.6 million BF – 54.0 million BF)[7] and therefore emissions calculations also vary. This highlights the importance of process and region specific LCA studies for accurate results and tailored recommendations. Comparison to literature also revealed that the benefits of carbon sequestration via cultivation reduces the impact of the system. Calculations indicated 6086.73 tons atmospheric carbon was sequestred in soils based on the incoming mass of wood processed by TAH in one calander year.

Limitations of this study include assumptions that are typically made in LCA studies. Since biodegradation contributed approximately 28.27% of emissions, this indicates assumptions regarding rate of biodegradation are sensitive. In this case 1% loss was assumed. Moisture Content (MC) also varies greatly across species, and it is recommended to measure MC across the process. The study's gate-to-gate boundary excludes hardwood timber cultivation, harvest, and transport as well as, end of life use of products. Thus, it is recommended to broaden the scope in future works, particularly cradle-to-gate to encompass the carbon neutrality of replacing fossil fuels with biomass during kiln drying.

Possible sites for emission reduction include limiting distance between stages of processing to reduce diesel usage in transportation equipment. Additionally, full conversion of all boilers to be biomass powered will reduce emissions due to sequestered carbon with the inclusion of tree cultivation. This will also reduce the yearly emissions from fossil fuel sources by 1012.17 tons, or 581296.766 kg of carbon.

6. References

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Appendix

A.1. Equations and conversions

Unit Conversions

The analysis for this project was conducted using the metric system. Results were converted to the imperial system for this report. The following list can be used for unit conversions.

1 kg...2.205 Ib

1 ton ....2000 Ib

1 kWh...3600 kJ

1 m^3 ....423.8 BF

Conversion Factors

$$°C * \frac{9}{5} + 32 = °F$$

$$°C + 273.15 = K$$

Mass of Biomass

Biomass data was listed in BF. As such, conversion to kg was necessary, shown below. A density of 2.0108 kg/BF was used.

$$1\ BF * \frac{2.0108\ kg}{BF} * \frac{2.205\ lb}{kg} = 4.4338\ lb \qquad 2$$

Since volume is affected by moisture content, the calculated mass would then also include water. Therefore, conversion to dry weight was necessary. Information on the moisture content of various biomass flows can be seen in section 7.2 of the appendix.

$$Dry\ mass = \frac{Total\ mass}{MC(db)+1} \qquad 3$$

Stoichiometry

The following equation was used for calculating emissions resulting from biodegradation and combustion of biomass. In both cases, complete combustion was assumed.

$$C_6H_{10}O_5 + 6\ O_2 \rightarrow 6\ CO_2 + 5\ H_2O$$

$$Biomass\ Combusted\ (kg) * \frac{0.444\ lb\ C}{1\ lb\ Biomass} = 0.444\ lb\ C \qquad 4$$

The following equation was used for calculating emissions resulting from the combustion of diesel. Complete combustion was assumed.

$$C_{12}H_{26} + 18.5\ O_2 \rightarrow 12\ CO_2 + 13\ H_2O$$

$$Dodecane\ Combusted\ (kg) * \frac{0.846\ lb\ C}{1\ lb\ Dodecane} = 0.846\ lb\ C$$ 5

The following equation was used for calculating emissions resulting from the combustion of propane. Complete combustion was assumed.

$$C_3H_8 + 5\ O_2 \rightarrow 3\ CO_2 + 4\ H_2O$$

$$Propane\ Combusted\ (kg) * \frac{0.817\ lb\ C}{1\ lb\ Propane} = 0.817\ lb\ C$$ 6

Carbon Sequestration

The ratio of aboveground to belowground carbon of the aforementioned study was 6.76. 64.5% of harvested wood was logwood and 35.5% pulpwood. Equation 7 shows the relationship between mass (*m*) of total logs, incoming logs (logwood), and pulpwood.

$$m_{total} = m_{logwood} + m_{pulpwood}$$

$$m_{total} = \frac{m_{logwood}}{0.645} = \frac{59{,}762.12\ tons}{0.645} = 92{,}654.45\ tons \qquad 7$$

From the total mass of harvested wood, the total mass of carbon (*C*) could be determined.

$$C_{total} = m_{total} * \frac{0.444\ ton\ C}{1\ ton\ Biomass} = 92{,}654.45\ tons * \frac{0.444\ ton\ C}{1\ ton\ Biomass} = 41{,}138.58\ tons \qquad 8$$

After determining total mass, the mass of belowground sequestered carbon could be determined using the ratio.

$$\frac{C_{total}}{C_{belowground}} = 6.76$$

$$C_{belowground} = \frac{C_{total}}{6.76} = \frac{41{,}138.58\ tons}{6.76} = 6085.59\ tons \qquad 9$$

Biodegradation

Biodegradation decay rate was calculated based on species in common between TAH and the study. This included Ash, Basswood, Oak, Maple, and Walnut. These species made up 70.18% of the total incoming volume of logs. Table A1 shows the calculation of the weighted average decay rate.

Table A1: Calculation of the weighted average decay rate.

Species	*Incoming Volume (BF)*	*Volume Fraction*	*Decay Rate*	*Weighted Decay Rate*
Ash	959794	8.49%	0.016800	0.001426
Basswood	11376	0.10%	0.044900	0.000045
Oak	9738383	86.13%	0.009300	0.008010
Maple	505	0.00%	0.036200	0.000002
Walnut	596609	5.28%	0.009700	0.000512
Total	**11306667**	**100.00%**		**0.009995**

Time of biodegradation was calculated based on the projected time for common wood species between TAH and the study to air dry. These included Ash, Red & White Oak, Maple, and Poplar. These species made up 78.80% of the total incoming volume of logs. Table A2 shows the calculation of the weighted average time to air dry.

Table A2: Calculated of the weighted average time to dry.

Species	*Incoming Volume (BF)*	*Vol. Fraction*	*Time to Air Dry (days)*	*Weighted Time to Air Dry (days)*
Ash	959794	7.56%	130	9.82
Red oak	4514044	35.56%	135	48.00
White oak	3544238	27.92%	165	46.06
Maple	505	0.00%	125	0.00
Poplar	3676499	28.96%	85	24.61
Total	**12695080**	**100.00%**		**128.51**

Kiln Energy Consumption

The heat provided by propane combustion was calculated using the equation below. A lower heating value (LHV) of 46.35 MJ/kg was used.

$$Heat_{Propane}\ (MJ) = Propane\ (kg) * LHV_{Propane} \qquad 9$$

To calculate the heat provided by biomass combustion, the LHV first had to be determined. This was done using the Gaur and Reede approximation (1995), seen below. X_i's are entered as mass percentages, and HHV is in MJ/kg db.

$$HHV = 0.3491\ X_C + 1.1783\ X_H + 0.1005\ X_S - 0.0151\ X_N - 0.1034\ X_O - 0.0211\ X_{ash} \qquad 10$$

LHV was then calculated using the following relationship. The latent heat of vaporization at 70 °F was used.

$$LHV = HHV - \frac{0.556\ kg\ H_2O}{kg\ C_6H_{10}O_5} * \frac{2.4509\ MJ}{kg\ H_2O} \qquad 11$$

Once LHV was determined, the following equation was used to determine energy generated assuming complete combustion, factoring in boiler efficiency (99%).

$$Heat_{Biomass}\ (MJ) = Biomass\ (kg) * LHV_{Biomass} * h_{boiler} \qquad 12$$

Kiln Heat Loss

Loss from biomass combustion was calculated using boiler efficiency. An efficiency of 99% was used.

$$Loss\ (MJ) = Heat_{Biomass}\ (MJ) * (1 - 0.99) \qquad 13$$

Loss from vents was calculated using the following equation. Absolute humidity was calculated using a psychrometric chart from Data, using the operating conditions for the kiln. To see information on the operating conditions for the kiln, see section 7.2.

$$Loss\ \left(\frac{Btu}{Ib\ H_2O}\right) = (T_{Kiln} - T_{\infty})(\frac{0.241 + 0.492\ H_{\infty}}{H_{Kiln} - H_{\infty}}) \qquad 14$$

Loss by conduction through walls was calculated using the following equation, based on a relationship found by Oregon State.

$$Loss_{Conduction} = Loss_{Vents} * 2 \qquad 15$$

Loss by conduction through pipes was calculated using the following equation.

Table A3: Loss by conduction through pipes.

Item	Value	Notes
Steam temperature (T_s)	244 °F	12 psig saturated steam
Ambient air (T_a)	80 °F	typical summer outdoor
Pipe OD (r_1)	12.75 in ⇒ 0.531 ft	12 in schedule-40 steel
Insulation thickness	2 in ⇒ r_2 = 0.698 ft	mineral wool k≈0.29 Btu · in / h · ft² · °F
Conductive resistance	R_cond = 1.80 h °F / Btu · ft	$\ln(r_2/r_1)/(2\pi k)$
Convective + radiative resistance (80 °F still air)	R_conv ≈ 0.05 h °F / Btu · ft	h_total ≈ 1.5 (NC) + 2.7 (rad) ≈ 4.2 Btu / h · ft² · °F
Total resistance	R_tot ≈ 1.85 h °F / Btu · ft	R_cond + R_conv
Heat loss per foot	Q' ≈ 88 Btu / h · ft	(T_s – T_a) / R_tot
Heat loss, 1 500 ft	≈ 1.3 × 10^5 Btu h^{-1}	88 × 1 500
Steam condensed	≈ 135–140 lb h^{-1}	Q / latent heat (≈ 970 Btu lb^{-1})

A.2. Assumptions

Biomass Flows

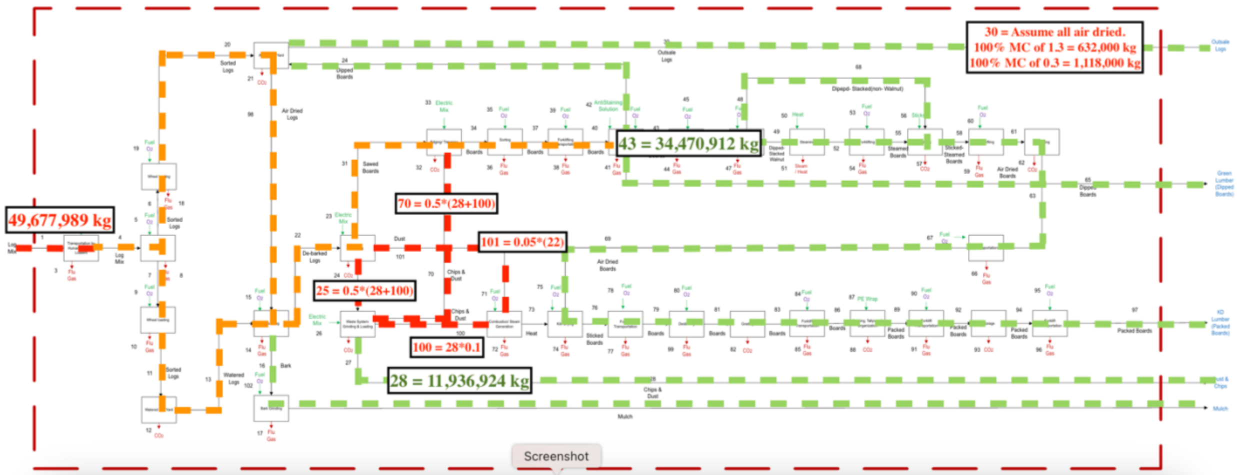
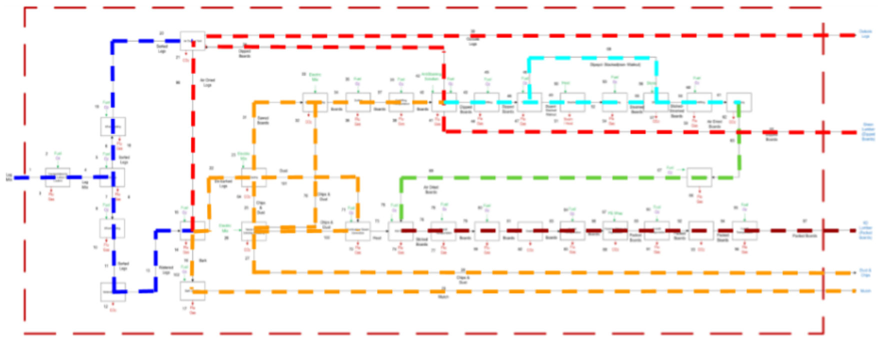


Figure A1: Assumed and known biomass flows within the process. Red streams are assumed, green known, and orange dependent upon assumed.

Figure A1 shows the assumed and known biomass flows within the process. An assumption was necessary due to a discrepancy between the calculated mass of incoming vs outgoing logs. It was decided to preserve the flows exiting the system boundary and, using the Solver add-on in excel, increase stream 1 to match. Accordingly, the mass of incoming green hardwood log was increased by a factor of 4.04, from 1.55×10^4 tons to 5.48×10^4 tons. Flow 31, or sawmill output, was also increased as it did not match output.

No information was available on streams 25, 70, 100, and 101. Their values were assumed as a percentage of neighboring streams (Figure A1).

Moisture Content



	Type	Avg MC (d.b.)
	Green/Submerged Logs	130.00%
	Air Dried (Pre-Kiln)	45.09%
	Air Dried + Submerged Boards (Post-Dip)	38.10%
	Air Dried + Submerged Boards (Pre-Dip)	32.70%
	Air Dried	30.00%
	Kiln Dried	9.29%

Figure A2: Moisture content of biomass throughout the process.

Figure A2 shows the moisture content of biomass throughout the process. Some flows were composed of biomass of varying moisture content. Where possible, yard data was used to determine the dry mass composition of each moisture content. If yard data was not available, the flow was assumed to be air dried. The moisture content of flows 43-61 were unknown and thus yard data for outgoing kiln dried lumber was used.

Kiln Operating Conditions

Table A4: Kiln operating conditions.

Variable	Value	Units
Avg Specific Heat of Air	1.00877	kJ/kg/K
Ambient Air	299.82	K
Kiln Air	273.15	K
Ambient Air Relative Humidity	50	
Kiln Air Exit Relative Humidity	14	
Ambient Absolute Humidity (H1)	0.011	Ib/Ib
Kiln Absolute Humidity (H2)	0.65	Ib/Ib

A.3. Emissions

Table A5: Annual carbon emissions per individual stream.

Process	Stream	Stream #	Carbon (kg/yr)
			Current
Log/Board Processing			
Debarking	Flu gas out	14	27742.67
Sawing	CO2 out	64	440.03
Edging/Trimming	CO2 out	32	105487.20
Dipping	Flu gas out	41	4403.60
Desticking	Flu gas out	99	4403.60
Combustion & Drying			
Combustion/Steam Generation	Flu gas out	72	1329402.19
Kiln Drying	Flu gas out	74	66187.42
Residue Processing			
Bark Grinding	Flu gas out	17	4403.60
Waste System	CO2 out	27	440.03
Transportation/Sorting			
Incoming Logs	Flu gas out	3	44224.72
Incoming Log Sorting	Flu gas out	8	25603.78
Wheel Loading	Flu gas out	10	24911.79
Wheel Loading	Flu gas out	18	39632.39
Pre-Dip Sorting	Flu gas out	36	4403.60
Pre-Dip Transport	Flu gas out	38	1132.35
Post-Dip Transport	Flu gas out	44	1132.35
Pre-Steam Transport	Flu gas out	47	1132.35
Post-Steam Transport	Flu gas out	54	1132.35
Post-Sticking Transport	Flu gas out	59	1132.35
Pre-Kiln Transport	Flu gas out	66	1132.35
Post-Kiln Transport	Flu gas out	77	4403.60
Post-Grading Transport	Flu gas out	85	4403.60
Pre-Storage Transport	Flu gas out	91	4403.60
Outgoing Transport	Flu gas out	96	4403.60
Biodegradation			
Air Dry Yard	CO2 out	21	85827.10
Pre-Kiln Air Dry	CO2 out	62	36054.36

A.4. Energy Use

Process Stage Energy Composition

Table A6: Energy composition for each stage of the process.

Process	Diesel	Propane	Coal	Natural Gas	Hydroelectric	Nuclear	Biomass	Other Renewables	Total
Combustion & Drying	0.54%	7.05%	0.00%	0.00%	0.00%	0.00%	92.41%	0.00%	100.00%
Log/Board Processing	32.82%	0.00%	10.27%	23.17%	6.84%	24.53%	0.00%	2.37%	100.00%
Transportation/Sorting	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%
Residue Processing	93.41%	0.00%	1.01%	2.27%	0.67%	2.41%	0.00%	0.23%	100.00%

Table A7: Respective stage use for each energy source.

Process	Diesel	Propane	Coal	Natural Gas	Hydroelectric	Nuclear	Biomass	Other Renewables
Combustion & Drying	2.64%	100.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
Log/Board Processing	17.43%	0.00%	99.59%	99.59%	99.59%	99.59%	0.00%	99.59%
Transportation/Sorting	77.83%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Residue Processing	2.10%	0.00%	0.41%	0.41%	0.41%	0.41%	0.00%	0.41%
Total:	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%

Table A8: Composition of fossil-fuel vs non fossil-fuel energy for each stage of the process.

Process	Fossil-Fuel	Non Fossil-Fuel	Total
Combustion & Drying	7.59%	92.41%	100.00%
Log/Board Processing	66.26%	33.74%	100.00%
Residue Processing	100.00%	0.00%	100.00%
Transportation/Sorting	96.69%	3.31%	100.00%

Table A9: Respective stage use of fossil-fuel vs non fossil-fuel energy.

Process	Fossil-Fuel	Non Fossil-Fuel
Combustion & Drying	24.44%	96.19%
Log/Board Processing	23.08%	3.80%
Residue Processing	51.05%	0.00%
Transportation/Sorting	1.43%	0.02%
Total:	100.00%	100.00%

TAH Grid Composition

Table A10: Duck River Electric grid mix.

Value	Units	Name
42.835	%	Duck River Electric Grid Mix (2023-2024) - Nuclear
28.000	%	Duck River Electric Grid Mix (2023-2024) - Natural Gas
15.420	%	Duck River Electric Grid Mix (2023-2024) - Coal
9.440	%	Duck River Electric Grid Mix (2023-2024) - Hydroelectric
2.307	%	Duck River Electric Grid Mix (2023-2024) - Null Power
1.393	%	Duck River Electric Grid Mix (2023-2024) - Wind
0.317	%	Duck River Electric Grid Mix (2023-2024) - Solar
0.174	%	Duck River Electric Grid Mix (2023-2024) - Landfill Gas
0.053	%	Duck River Electric Grid Mix (2023-2024) - Biogas
0.001	%	Duck River Electric Grid Mix (2023-2024) - Biomass
0.001	%	Duck River Electric Grid Mix (2023-2024) - Diesel

Energy Loss in Drying

A contributing factor to the high energy demand of drying is loss. Of the total $14.60x10^6$ kWh of energy generated through combustion, $1.23x10^6$ kWh are lost. This measures to be 8.41% of the total energy generated (by combustion) (Figure A3).

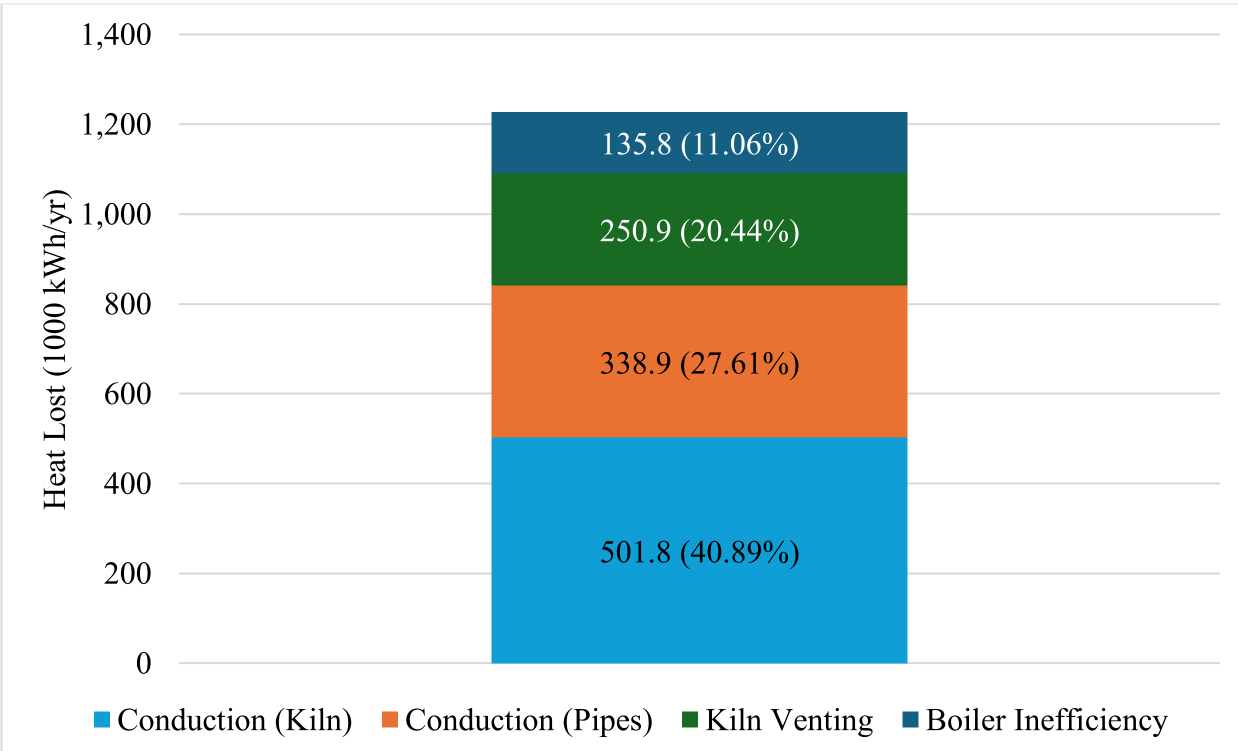


Figure A3: Annual drying-related loss contribution analysis.

Allohverdi, T.; Saffron, C.; Pokharel, R.; and Wesley Broda, W. 2025, A Life Cycle Analysis of the Sawmilling Process of the Thompson Appalachian Hardwood Facility. Department of Forestry, Michigan State University, East Lansing, MI.

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