CORRIM: Phase II Final Report

Module L

Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Southeastern United States

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Executive Summary

The goal of this study was to gain an understanding of the environmental impact of hardwood lumber production through a gate-to-gate life-cycle inventory (LCI) of hardwood sawmills in the Southeastern United States (SE). Primary mill data were collected per Consortium on Research for Renewable Industrial Materials (CORRIM) Research Guidelines. Life-cycle impact assessment is beyond the scope of the study.

A mill questionnaire was used to survey 12 hardwood sawmills across the SE region. Total annual hardwood lumber production for this region, in 2005 and 2006, was 9.25 million m^3 (3.79 billion board feet (ft)[1]) and 8.76 million m^3 (3.59 billion bf), respectively (USCB 2007; 2008). Annual production for the 12 sawmills surveyed during 2005 and 2006 was greater than 576 thousand m^3 (236 million bf) of rough green lumber, 6% of the total hardwood annual lumber production of this region for this 2-year period. Most of the rough green hardwood lumber was not Kiln dry and planed (surfaced) on-site prior to shipping. The surveyed mills had an annual production for rough dry and planed dry lumber of 365 thousand m^3 (171 million bf) and 121 thousand m^3 (71.8 million bf). The mill questionnaire separated hardwood lumber manufacturing into four main unit processes: logyard, sawing, drying, and planing. The energy generation process, including boiler operations, was considered an auxiliary process. Mill data were weighted-average on a per unit basis of 1.0 m^3 of planed dry lumber (600 oven dry (OD) kg/m^3) to find material flows and energy use. Material flow and energy use data were entered into modeling software (SimaPro 7, PRé Consultants, Amersfoort, Netherlands) to determine environmental impact.

A mass conversion of 46.5% was found from producing planed (surfaced) dry lumber from a hardwood log. Process energy consumption of 631 MJ of electricity (grid and on-site) and 5,167 MJ/m^3 from on-site fuels[2] were determined for the manufacturing of planed dry hardwood lumber from incoming logs. Of the total electricity, grid electricity and on-site (cogeneration) electricity provided 598 and 33 MJ, respectively. Of the total value from burning on-site fuels per cubic meter of planed dry lumber, 4,678-MJ input into drying, 334-MJ input into on-site electrical generation, and 155-MJ input into plant heat. Cogeneration electrical efficiency was at an estimated 10%. Burning green wood residues on-site generated most of the energy. Some important weighted-averaged mill features are a log diameter of 0.396-m (15.6-in.), production kiln capacity of 1.00 thousand m^3 (425 thousand bf (MBF)), and mill volume of 76.4 thousand m^3 (31.3 million bf[1]) for the 12 mills surveyed. Also, pulp chips are the greatest proportion of wood residue produced. The wood species examined were red and white oak (over half), hard and soft maple, poplar, cottonwood, ash, gum, pecan, hickory, hackberry, cypress, and some miscellaneous species. Emission data produced through modeling estimated total biomass (biogenic) and fossil (anthropogenic) carbon dioxide production of 424 and 131 kg/m^3, respectively, considering all impacts. A cubic meter of planed dry hardwood lumber stores 1,164-kg CO_2equivalents as a final product.

The following main conclusions are based on the life-cycle inventory:

Burning fuel for energy generates CO2. Nearly all energy burned on-site for manufacturing hardwood lumber comes from woody biomass. Burning biomass for energy does not contribute to increasing atmospheric CO2 provided forests are regrowing and reabsorbing the emitted CO2.

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[1] One nominal board foot equals 1 by 12 by 12 in. (25 by 300 by 300 mm); 2.44 actual m^3 per nominal thousand board feet conversion.
[2] The value for on-site energy was based on higher heating values. No efficiencies assumed. All on-site energy was allocated to the planed dry lumber.

The amount of carbon stored in hardwood lumber exceeds the fossil carbon emissions by a factor of 9. Therefore, as long as hardwood lumber and its carbon stay in products held in end uses the carbon stored will exceed the fossil carbon emitted in manufacturing.

Increasing on-site wood fuel consumption would reduce fossil greenhouse gases but increase other gases, especially particulate emissions. Particulate matter can be captured prior to release to the atmosphere using commercially available technology but not without increased costs.

The region selected for production affects the environmental impact of this product because coal represents the greatest proportion of off-site material used for electrical power generation in the SE region. Most power in the Pacific Northwest is produced from hydro and then natural gas, whereas most power in the Southeast is produced from coal and uranium just as in the Northeast/North Central region.

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1.0 Introduction

Hardwood lumber from species in the Southeastern United States (SE) is used primarily for pallets, crossties, flooring, millwork, cabinets, and furniture. Total annual U.S. hardwood lumber production in 2005 and 2006 was 26.4 million m^3 (11.2 billion bf) and 26.0 million m^3 (11.0 billion bf), respectively. Most hardwood lumber is consumed domestically, but an estimated 3.12 million m^3 (1.32 billion bf) was exported in 2006. Also, 882 thousand m^3 (374 million bf) was imported in 2006 (USCB 2008). Domestic hardwood lumber production occurs mostly in the eastern United States and split roughly in half between the SE and the Northeastern and North Central United States (NE/NC). A smaller percentage, approximately 3.3%, of hardwood lumber production occurs in the Pacific Northwest (PNW). Rough green hardwood lumber is used in pallets and crossties whereas most of the planed dry lumber is converted into building products for new construction and repair and remodeling of existing buildings.

Energy consumption and environmental impact of manufacturing residential building products are playing an increasingly important role in the building industry because of increased public awareness of environmental issues. In the construction and remodeling industry, consumption increased from 6.23 million m^3 (2.64 billion bf) in 1992 to 9.84 million m^3 (4.17 billion bf) of hardwood lumber in the United States (Luppold and Bumgardner 2008). One major reason for this huge consumption is an increase in average building size for residential buildings. The average-size single-family residential home increased from 193 m^2 (2,075 ft^2) in 1991 to 234 m^2 (2,521 ft^2) in 2007, a 25% increase. Another factor is the doubling in number of single-family residential buildings constructed from 1991 to 2005; this is less of a factor recently because of a large drop in single-family residential construction seasonally adjusted annual rate, from a high of 1.64 million in 2005 to 0.490 million in July 2010 (USCB 2010). However, green building is expected to play an increasing role in the residential building industry because of an increase in the environmental concerns of consumers.

"Green building" is defined as the practice of improving energy efficiency for materials, construction, and operation while reducing the overall environmental impact of buildings. Two percent ($7.4 billion) of new residential starts in 2005 were classified as "green buildings," and this minimum market share is expected to increase to 5% ($19 billion) by 2010 (MHC 2006, Murray 2008). Developing a sound policy for building practices, especially for green building, must be a priority if the United States is to decrease its environmental burden on the world's resources. However, scientific evidence is needed to evaluate claims for green building materials.

Accurate baseline life-cycle inventory (LCI) data are needed as a part of this broader scientific approach for determining building styles, type of construction materials, and product improvements with a focus on reducing environmental burdens. This LCI study provided useful data by examining the environmental impact of hardwood lumber production in the SE. In addition, these data can be interconnected into the U.S. LCI database managed by the National Renewable Energy Laboratory to complete a life-cycle assessment of hardwood lumber-related wood products (NREL 2010).

LCI provides an accounting of the energy and waste associated with the creation of a product through use and disposal. In this study, the gate-to-gate LCI tracked hardwood lumber production from hardwood logs stored in the log yard to planed dry lumber including transportation of logs from the forest to the mill. Life-cycle assessment (LCA) is a broader examination of the environmental and economic effects of a product at every stage of its existence, from harvesting to disposal and beyond. A cradle-to-grave life cycle assessment is beyond the scope of this study. In this LCI study, tracking the material flow of hardwood lumber is needed for an accurate survey of the different unit processes.

Material flow is tracked from raw material—hardwood logs—to planed (surfaced) dry lumber, the final product. Rough green (freshly cut) lumber sawn from hardwood logs is typically dried in conventional dry kilns using wood residues (wood biomass) and fossil fuels as heat sources. It is estimated that nearly 90% of all hardwood lumber dried in the United States uses energy produced with wood biomass from the milling processes (Denig et al. 2000, Bergman and Bowe 2008). Not all rough green hardwood lumber is Kiln dry. The sawing process consumes the highest percentage of “electrical” energy. Prior to drying the lumber, the boards are stickered (separated by thin wood strips) and stacked to aid drying and prevent drying defects. The drying process consumes 70% to 80% of the “total” energy required for producing hardwood lumber (Comstock 1975). Total energy includes both electrical and thermal. Some rough dry lumber is planed or skip planed after drying is complete.

The goal of this study is to document the LCI of planed dry lumber production from hardwood logs and determine material flow, energy use, and emissions for the hardwood lumber manufacturing process on a per unit basis for the southeastern United States (SE) (Figure 1.1). Collected primary data collected through questionnaires mailed to lumber mills; secondary data were collected from peer-reviewed literature per Consortium for Research on Renewable Industrial Material (CORRIM) guidelines (CORRIM 2001). We calculated material and energy balances by a spreadsheet algorithm using data from primary and secondary data sources. From these material and energy values, environmental impacts were estimated by modeling the emissions through SimaPro 7 software (PRé Consultants, Amersfoort, Netherlands) (PRé Consultants 2010).SimaPro was used in previous CORRIM-initiated LCI projects: hardwood lumber (Bergman and Bowe 2008), softwood lumber (Milota et al. 2005), softwood plywood (Wilson and Sakimoto 2005), I-joist production (Wilson and Dancer 2005a), glued-laminated timbers (Puettmann and Wilson 2005), and laminated veneer lumber (Wilson and Dancer 2005b).

Figure 1.1. The shaded area was selected for life-cycle inventory of hardwood lumber production in the Southeastern United States.

1.1 Annual Lumber Production

For the SE region, annual hardwood lumber production values for 2005 to 2007 (Figure 1.2). Arkansas, Georgia, Mississippi, North Carolina, and Tennessee are the major hardwood-lumber-producing states in the SE. Eight states in this region are represented. Total 2006 annual hardwood lumber production for this area is 8.76 million m^3 (3.59 billion bf) (USCB 2007, 2008). The 12 mills produced 576 thousand m^3 (236 million bf[3]) rough green lumber that represents 6% of the total annual 2006 U.S. production from this region. This 6% value exceeded the minimum CORRIM protocol guideline for data representation

[3] 2.44 m^3/MBF rough green lumber

(CORRIM 2010). Mills surveyed were from Alabama, Louisiana, Mississippi, North Carolina, and Tennessee and the 2006 hardwood lumber production just for these five states (the surveyed region) was 6.08 million m^3 (2.49 billion bf). Just using the five states where the surveyed mills were located, surveyed mill production represented over 9% of total production.

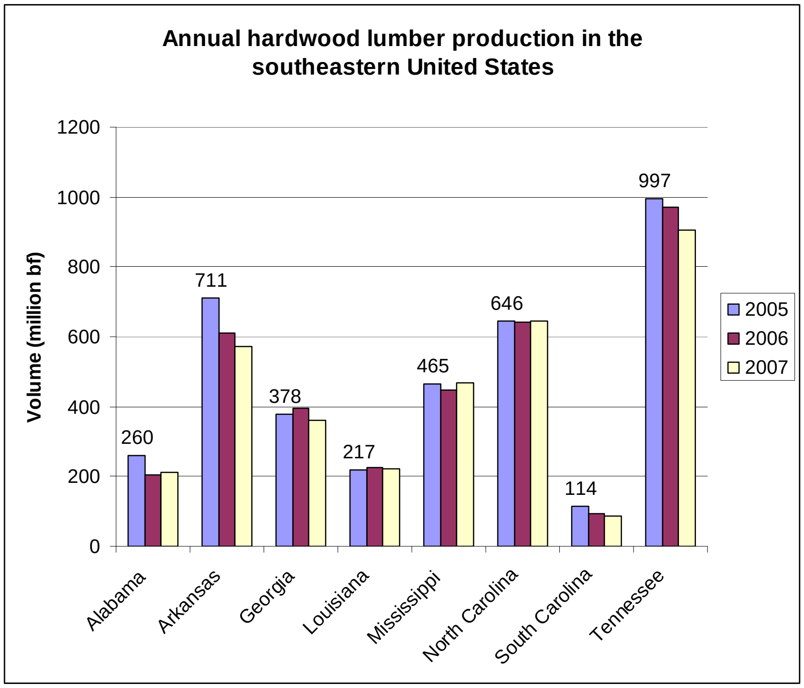

Figure 1.2. Annual hardwood lumber production by state for the past 3 years. (Sources: USCB 2007, USCB 2008.)

1.2 Mill Questionnaire

We developed a mill questionnaire (survey instrument) based on other LCI lumber studies that was adapted specifically to address the production of hardwood lumber. A draft questionnaire was critically reviewed by a CORRIM representative (James Wilson, Oregon State University). The questionnaire was split into two sections. Section 1 (Appendix A-1) of the questionnaire, “Introduction and Questionnaire,” and was sent to the mills, and section 2 (Appendix A-2) was removed to keep the questionnaire simple. Section 2 had information describing the questionnaire but did not request primary mill data. By omitting section 2, we hoped to minimize confusion and increase the likelihood that mills would complete the questionnaire. Therefore, an edited version was mailed primarily to members of the Hardwood Manufacturer’s Association (HMA). Mills from HMA were chosen because HMA members are representative of the hardwood industry in the SE region. The HMA executive vice-president was supportive of the project and helpful in identifying participating mills. Twelve hardwood lumber mills completed the questionnaire after several follow-up calls. Although the number of mills surveyed may be small (n = 12) compared with a “typical” mail survey, the level of detail and quantity of primary mill data for a CORRIM study is very high (Appendix A-1). Each mill contributed a substantial amount of time completing the questionnaire, ranging from 8 to 20 hours, with an average of 12 hours including the follow-up questions.

Material flow was given in oven-dried (OD) weight per cubic meter of planed dry lumber. As in previous CORRIM reports (Milota et al. 2004), data from the mill questionnaire were weighted-averaged using

$$\overline{P}_{\text{weighted}} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i}$$

Where $\overline{P}_{\text{weighted}}$ is the weighted average of the values reported by the mills, P_i is the reported mill value, and x_i is the fraction of the mill's value to total production for that specific value.

2.0 Unit Process Approach

2.1 Hardwood Lumber Manufacturing and the Four Main Unit Processes

There are four main unit processes in producing hardwood lumber—logyard, sawing, drying, and planing (Figure 2.1)—with energy generation as an auxiliary process. We chose mass allocation because the highest volume product has the highest economic value. This was true for all unit processes. Production starts with hardwood logs that are typically trucked to the sawmill and stored on the log yard until sawn. Logs may be stored dry or wet, depending on species and season. In the sawing process, incoming hardwood logs (the raw material) are sawn into mostly 25- and 50-mm- (1- and 2-in.-) thick rough green (freshly cut) lumber of random widths and mostly 2.44 to 3.66-m to (8 to 12-ft) lengths. Dimension sizes are nominal. Once the rough green lumber is scaled (to measure production volume) and stickered for drying, the lumber is typically dried to 6% to 8% moisture content on a dry basis (MC_{DB}) using mostly energy-intensive drying methods such as kiln drying, although some air and pre-drying drying does occur. After drying, the rough dry lumber is planed to the dimension required for the final product. The energy generation process provides heat with a small amount of electricity, primarily produced on-site for these three processes. Co-products are both sold and used for on-site energy generation. In this study, by-products are also referred to as co-products because all wood residuals are used either on-site or sold off-site. In this LCI study, when referring to logs, lumber, and other co-products, the term green was used in the context of freshly cut material that is 85% MC_{DB}.

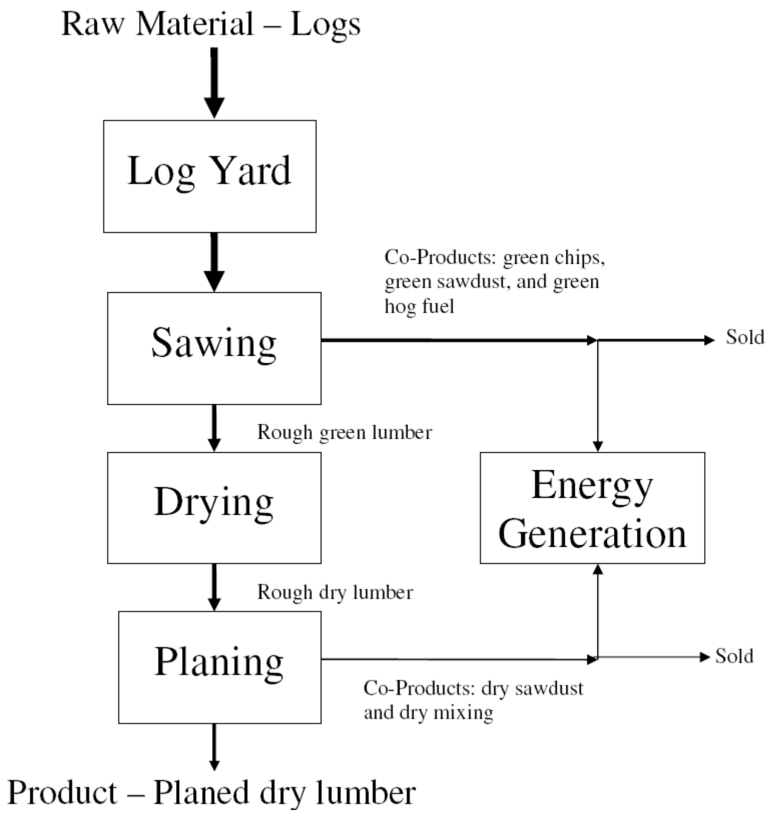

Figure 0-1. Material flow for the four unit processes of hardwood lumber manufacturing.

2.1.1 Logyard

This unit process begins with logs in the mill yard and includes the following operations:

- Sorting and storing logs; storage wet or dry, depending on season and species
- In-yard transportation of logs from point of unloading to log deck storage
- In-yard transportation of logs from log deck storage to the sawmill infeed and log bucking saw and/or debarker
- Transporting logs from forest landing to log yard

2.1.2 Sawing

This unit process begins with logs at the debarker and includes the following operations:

- Debarking logs (co-product is bark) and merchandise long sawlogs into short sawlogs at bucking station (cutoff saw); produces some log trim ends
- Breaking down logs (sawing) into rough green lumber and residues (slabs, edgings, sawdust, and trim ends ground into chips)
    - Slabs are sections of wood cut on circular or band head rigs from the outside portions of logs when opening up the log on each of four sides; slabs do not have square edges, and one face is waney (might have bark and is not flat).
    - Edgings are strips removed by a machine called an edger that produces a square-edged board from flitches (waney pieces of lumber).
    - Trim ends, slabs, and edging strips are processed at the chipper, producing clean (bark-free) pulp chips.
- Trimming, grading, and sorting

- Stacking, stickering, and in-yard transporting rough lumber to kilns, final customer, or planer facilities; may be dipped to prevent staining
- Sawfiling and maintenance all sawmill equipment and yard transportation vehicles
- Treating process air, liquids, and solids

Outputs of this unit process are sawn rough green lumber and wood residues from the sawing process; bark, sawdust, slabs, edgings, and chips (hog fuel is a mixture of the wood residues produced). Most green wood residues are sold (77%) as a co-product; others (17%), especially sawdust, are combusted as fuel, mostly to dry lumber. The remaining wood residues (6%) produce salable goods such as mulch (bark) and pulp chips.

2.1.3 Drying

This unit process begins with rough green lumber and includes the following operations:

- Loading stickered lumber into the following facilities, depending on species, season, and equipment
  - Air drying yards
  - Pre-dryers
  - Dry kilns
- Drying, equalizing, and conditioning lumber within the kiln
- Maintaining all kiln equipment and related yard transportation vehicles
- Treating process air, liquids, and solids
- Unloading and transporting kiln-dried lumber to the planer mill or final customer

The output of this unit process is rough dry lumber, the majority of this material transported by forklift to the planer mill. Drying generates most of the volatile organic compounds (VOCs) generated on-site and uses the most energy produced on-site from both wood and fossil fuel combustion. For the 12 surveyed mills, initial MC_{DB} was 85% for rough green lumber and on average 8% for rough dry lumber. Different drying methods are used depending on species, lumber thickness, lumber grade, final use, and available wood residue markets. A typical sawmill uses a kiln schedule when drying lumber to maintain high quality by preventing drying defects. Most rough green lumber (about 63%) is Kiln dry at the mill.

2.1.4 Planing

This unit process begins with stickered, rough dry lumber and includes the following operations:

- Unstickering and/or unstacking lumber
- Ripping, grading, and sorting lumber
- Planing (surfacing) lumber
- Stacking, strapping, and packaging lumber
- Transporting lumber within the planer mill and loading for shipping
- Maintaining all planer equipment and associated yard transportation vehicles
- Treating process air, liquids, and solids

The output of this unit process is surfaced and packaged lumber, sorted by type, size, and grade as well as planer shavings, sawdust, and/or lumber trim ends. This process is the final stage of manufacturing. About 66% of dry wood residue is burned on-site in the boilers for energy, whereas the rest is sold as co-products. Some planed lumber is only blanked or skip (hit or miss) planed. For instance, secondary manufacturers such as hardwood moulding companies also plane a small portion of rough dry lumber. Only a small portion of rough green lumber that is Kiln dry is planed at the mill, about 21%.

2.1.5 Auxiliary energy generation

This auxiliary process provides heat and in some cases electricity for use in other parts of the mill. A fuel such as wood or natural gas is burned; green and kiln-dried wood residue from the sawing process generates most of the thermal energy used at the plant. The thermal energy is typically in the form of steam that is used for the dry kilns and facility heating. The second source of energy used on-site is off-site grid electricity. Also, emissions from grid electricity are released off-site.

This process involves the following operations:

- Handling fuel
- Adding water to the boiler (i.e., make-up water)
- Adding chemicals at the boiler or to steam lines
- Distributing steam
- Distributing electricity
- Treating process air, liquids, and solids

Outputs of this auxiliary process are steam and hot water from boilers, combustion gases for drying, electricity from cogeneration units and solid waste (wood ash), and air emissions (e.g., CO_2, CO) from combustion.

2.2 Functional Unit

Material flows, energy use, and emission data are standardized to a per-unit volume basis for 1.0 m^3 of planed dry lumber, the final product of the hardwood lumber manufacturing process. A typical conversion from cubic meters to thousand board feet (MBF) is 0.424 (2.36 m^3/MBF), which does not address differences between nominal and actual dimensions that are common in the lumber industry (USCB 2008). The value of 2.36 m^3/MBF is based on a board foot equaling 1 by 12 by 12 in. (25 by 300 by 300 mm). In this study, 1 m^3 of planed dry lumber equals 0.595 nominal MBF (1.68 m^3/MBF). The U.S. industry standard uses nominal dimensions, and commodity lumber is sold by variations of MBF. Rough green lumber and rough dry lumber are assumed to be 2.13 and 2.44 m^3/nominal MBF (Bergman 2010, Fonseca 2005). Allocating all material and energy on a per unit basis of 1.0 m^3 planed dry lumber standardizes the results to meet ISO standards, and the unit processes can be used to construct a cradle-to-gate LCI and LCAs (ISO 2006a,b; CORRIM 2010).

2.3 System Boundaries

Boundary selection is important because the material and energy that cross this boundary must be accounted for (Figure 2.2) in the gate-to-gate life-cycle inventory. Two boundaries are defined by CORRIM (Wilson and Sakimoto 2005) and used to track the environmental impact of hardwood lumber production. One is the total (cumulative) system boundary (solid line in Fig. 2.2), which includes both on-site and off-site emissions for all material and energy consumed. This includes the fuel resources used for the production of energy and electricity and is part of this LCI. The site-system boundary (dotted line in Fig 2.2) is the environmental impact for emissions developed just at the hardwood sawmill (i.e., on-site) from the four unit processes. Examples of off-site emissions are grid electricity production, transportation of logs to the mill, and fuels produced off-site but used on-site.

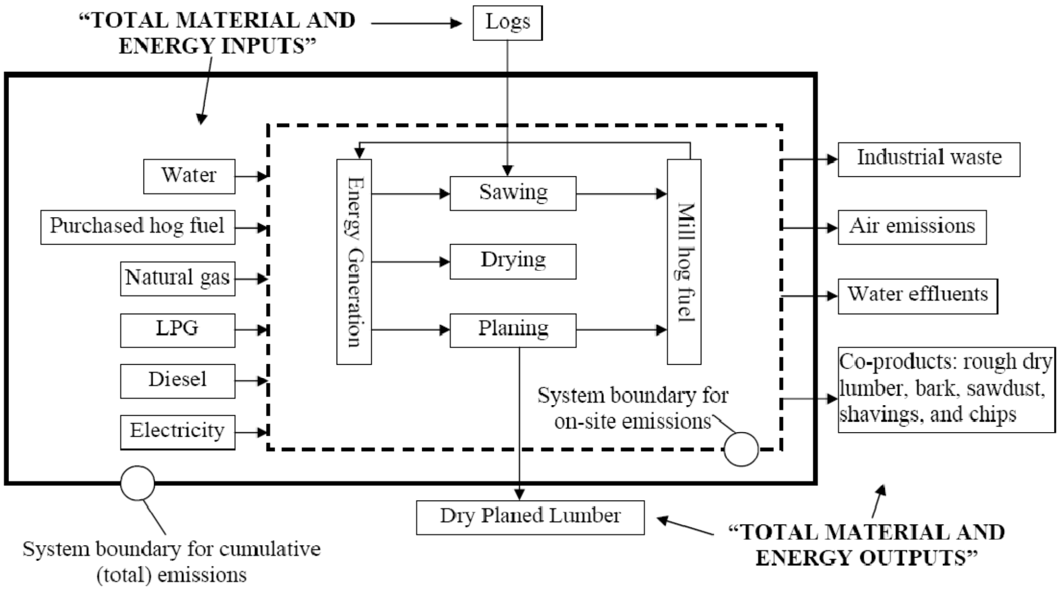

Figure 2.2. System boundaries for hardwood lumber production.

2.4 Project Assumptions and Limitations

Surveyed mills that reported all but one mill used the Doyle log rule to scale logs whereas one mill used the International ¼-log rule. Logs are stick scaled for both methods. The 12 mills surveyed gave log inputs in MBF. Common U.S. log rules estimate the green lumber board footage that might be sawn from a log, whereas lumber board foot tally provides the nominal green lumber volume produced from the log. Most other countries, including European countries, use a cubic log scale that measures the actual log volume (minus the bark).

The accuracy of U.S. log rules varies with log diameter, taper, type of sawing method, type of products sawn, and sawing efficiencies. Because of inaccuracies of log rules, small-diameter logs typically recover more lumber for a given log than the log rule predicts in comparison with large-diameter logs. The volume difference between the log scale and board foot lumber tally is referred to as either overrun or underrun, depending on whether the lumber tally or the log scale is greater (if the lumber tally is greater, there is an overrun). In this study, a mill weighted-averaged 26% overrun was estimated from scaling the incoming logs and the resultant rough green lumber tally. An average log conversion of 5.32 m^3/MBF was calculated based on a weighted-averaged log diameter of 15.6 in. reported, with a range from 14 to 20 in., from four of the twelve participating mills and assuming all lengths (Fonseca 2005). Also, a green log volume of 2.44 m^3 was calculated based on 1,287 OD kg of incoming wood volume on a per unit basis and a green specific gravity of 0.528. Furthermore, a 85%MC_{DB} was assumed for the incoming wood to the mill gate therefore a green wood log density of 977 kg/m^3 was calculated.

Green and dry wood density and specific gravity values found in the *Hardwoods of North America* (Alden 1995) for the 12 major wood species were used to convert between mass and volume bases. Some air drying occurred after sawing and prior to drying. Weighted green (85% MC_{DB}) and Kiln dry (12% MC_{DB}) specific gravity of 0.528 and 0.590 were calculated from literature values based on the species percentage. Specific gravity of 0.600 at 8% MC_{DB} was found by interpolated from the 12% MC value. 8% MC_{DB} was the final MC for Kiln dry lumber. Weighted densities of 977 kg/m^3 (61.0 lb/ft^3) and 648 kg/m^3 (40.4 lb/ft^3) were used for green and kiln dry lumber, respectively.

As part of the CORRIM protocol for ensuring data quality, an overall "wood balance" is required to fall within 5% from material input to material output. Log mass was calculated based on the previous assumption of 5.32 m^3/MBF and an average green density of 977 kg/m^3. In this study, a 1.3% difference was calculated for the overall wood mass balance, falling within the CORRIM protocol. Additionally, a 1.2% difference was calculated before and after sawing and a 1.3% difference before and after planing.

Higher heating value (HHV) is used to convert volume or mass basis of a fuel to its energy value. HHV represents the energy content of a fuel with the combustion products such as water vapor brought to 25 °C (77 °F), whereas lower heating value (LHV) ignores the energy produced by the combustion of hydrogen in fuel. HHV is the preferred method in the United States.

A standard check was conducted for energy use in the kiln drying of hardwood lumber. This study considered energy used on-site that included drying lumber but also energy for plant heating and electrical co-generation. These sub-processes are typically not associated with values found in previous studies when calculating energy used in drying. Therefore, energy for plant heating and electrical co-generation was not included in the following energy checks:

Total energy required to kiln dry 1.0 m^3 rough green lumber was found using the below equation, literature values on kiln operations, and the following inputs: MC_{DBo} of 85% and MC_{MCf} of 8%. Literature values include boiler efficiency of 66.7%, kiln efficiency of 50%, and 15.0 MJ of energy to remove 1% moisture from 1.0 m^3 rough green hardwood lumber[4] (Wengert 1980). A total energy consumption of 5,006 MJ/m^3 (7.98 million Btu/MBF) planed dry lumber was calculated for kiln drying rough green lumber . We calculated that an estimated energy value of 4,679 MJ/m^3 (7.46 million Btu/MBF) from actual mill data resulted in a 6.8% difference between the literature and the actual values.

$$E_{Total} = \frac{\left(MC_{DB_o} - MC_{DB_f}\right) * EP}{\varepsilon_{Boiler} * \varepsilon_{Kiln}}$$

where
E_{Total} is the total energy consumed to dry 1 m^3 rough green lumber,
MC_{DBo} and MC_{MCf} are the initial and final MC of the rough green lumber,
EP is the energy required to remove 1% moisture from the rough green lumber, and
ε_{Boiler} and ε_{Kiln} are the boiler and kiln efficiency values.

Energy use varied for the 12 mills drying lumber. We estimated cogeneration and plant heating consumption at 6.5% and 3.0 % of total process energy, respectively. We assumed an average technology with processes producing similar outputs in North America for modeling the environmental burden.

Logging transportation data assumed the same number of fully loaded trucks as empty trucks because logging trucks are usually built for hauling logs, not for hauling either lumber or wood residue. Each logging truck hauled about 5,500 bf hardwood logs or 55 tons (10 tons logs per MBF lumber). Six mills (50%) did not report logging transportation data and were not included. Logging trucks were assumed to be empty upon return to the logging site.

Purchased wood fuel transportation data was from one mill that burned 100% of the total purchased wood fuel trucked. No other mill used purchased wood fuel.

Water used on-site typically was ground water, typically wells, and primarily used for sprinkling logs and for make-up boiler water. Seven mills did not report water consumption and were not weighted-averaged.

[4] 34,561 BTU required for 1% moisture reduction per MBF

The LCI study covered one full year during the period 2005 and 2006 and depended on when an operational (fiscal) year started at each company. The geographical area covered the SE region shown in Figure 1.1.

We collected primary mill data through a critically reviewed questionnaire in accordance with ISO standards and CORRIM research guidelines. Missing values were not weighted-averaged for a particular process per ISO standards.

Most of the mills surveyed were medium- to large-size facilities. Many small-size mills (less than 1 million bf) do exist but typically provide only custom wood products. In addition, smaller mills tended not to keep accurate production records and even some of the larger hardwood mills did not have the primary mill data requested.

Primary data indicated that the species represented were red and white oaks (*Quercus spp.*), hard and soft maples (*Acer* spp.), hackberry (*Celtis* spp.), pecan (*Craya* spp.), hickory (*Carya* spp.), bald cypress (*Taxodium distichum*), yellow poplar (*Liriodendron tulipifera*), cottonwood (*Populus* spp.), ash (*Fraxinus* spp.), and sweetgum (*Liquidambar styraciflua*). As shown in Table 2.1, these percentages varied notably from reported data, with white oak percentages higher and red oak percentages lower compared with 2006 U.S. census figures (USCB 2008). This difference probably was due to market fluctuations or surveying only 12 mills.

Table 2.1. Species hardwood lumber production for the Southeastern United States compared with LCI survey data.

		Lumber production (%)	
	Species	**LCI survey data (*n* = 12)**	**U.S. Census Bureau[a]**
1	Red oak (mix)	50.0	37.9
2	White oak (mix)	11.7	18.3
3	Hard maple (mix)	1.77	7.77
4	Soft maple (mix)	0.42	5.74
5	Hackberry	1.67	*
6	Pecan	1.25	1.32
7	Hickory	0.45	1.32
8	Bald cypress	3.85	*
9	Poplar	16.5	16.9
10	Cottonwood (mix)	0.89	1.23
11	Ash (mix)	4.21	3.42
12	Sweetgum	1.99	3.41
13	Miscellaneous	5.33	2.72
	Total	100	100

[a]USCB (2008).

*Not reported.

The type of species processed at individual mills would alter the density of the final product, not the volume. We noted a range of 0.38 (cottonwood) to 0.72 (white oak) oven dry specific gravity for all the different wood species.

The Franklin database, not primary mill data, provided boiler emission data as part of SimaPro 7 (FAL 2003a, b).

Hardwood lumber industry considers bald cypress (*Taxodium distichum*) a hardwood, although it is a softwood species.

2.5 Modeling Software Selection

Modeling software was needed to generate air, water, and land emission data from the weighted-averaged results of material flow and energy use and type for hardwood lumber manufacturing in a systematic and transparent way. Because the LCI practitioner adhered to the basic four steps of life-cycle research—goal and scope definition, inventory analysis, impact analysis, and interpretation—the software also needed to follow the ISO 14040 protocols related to environmental management. SimaPro was the modeling software selected, and SimaPro training was completed in December 2004.

SimaPro 7 follows the ISO 14040 standards for environmental management and documentation. Other software programs for life-cycle analysis such as GaBi were considered, but SimaPro is the software preferred by CORRIM and was used in Phase I of the other life-cycle inventory projects sponsored by CORRIM. Phase I projects dealt mostly with forest resources and residential construction in the U.S. Pacific Northwest and Southeast. SimaPro 7 was developed in the Netherlands and has an installed Franklin Associate (FAL) database that uses North America production data. The FAL database tracked energy use and material flow in this study (FAL 2003a, b). SimaPro allows the use of the unit process approach. In this LCI study, using the unit process approach was preferred because it is more rigorous and transparent than the simple system process approach. This transparency allows the tracking of all individual unit processes. SimaPro contains a database for a large number of processes such as boilers (energy generation), grid electricity, and transport fuels. The database is broken into three main sections: project data, library data, and general data. In this study, the project data section is where all new LCI data were entered. Library data were the sources for an individual project, and the Franklin Associate (FAL) database library was selected for this LCI. The last section (general data) contained common data such as substance data and unit conversion factors (PRé Consultants 2008).

2.6 Material Properties

2.6.1 Wood species composition

A number of commercial hardwood species are sawn in the SE region. Often, several species within one species group are averaged together to find specific gravity and densities; for example, the red oak group has nine such species:
scarlet (*Quercus coccinea*), southern (*Q. falcate*), cherrybark (*Q. falcate var. pagodifolia*), laurel (*Q. laurifolia*), water (*Q. nigra*), pin (*Q. palustris*), willow (*Q. phellos*), northern (*Q. rubra*), and black (*Q. velutina*). Other species groups with multiple species are white oak (6): white (*Q. alba*), swamp white oak (*Q. bicolor*), bur (*Q. macrocarpa*), swamp chestnut (*Q. michauxii*), chestnut (*Q. prinus*), and post (*Q. stellata*); hard maples (2): sugar (*Acer saccharum*) and black (*A. nigrum*); soft maples (2): red (*A. rubrum*) and silver (*A. saccharinum*); cottonwood (3): balsam poplar (*Populus balsamifera*), eastern (*P. deltoids*), and black (*P. tricocarpa*); and ash (3): white (*Fraxinus americana*), black (*F. nigra*) and green (*F. pennsylvanica*).
Table 2.1 shows the breakdown of primary mill data compared with U.S. Census Bureau data for the Eastern hardwood region reported as an aggregate for the entire SE region.

Table 2.2. Physical data for species sawn in the SE United States

	Species	Distribution (%)	Specific gravity[a] Green volume[b]	12% MC_{DB} volume
1	Red oak (mix)	50.01	0.57	0.65
2	White oak (mix)	11.69	0.60	0.67
3	Hard Maple (mix)	1.77	0.54	0.60
4	Soft Maple (mix)	0.42	0.47	0.51
5	Hackberry	1.67	0.49	0.53
6	Pecan	1.25	0.60	0.66
7	Hickory	0.45	0.64	0.72
8	Bald cypress	3.85	0.42	0.46
9	Poplar	16.47	0.40	0.42
10	Cottonwood (mix)	0.89	0.33	0.36
11	Ash (mix)	4.21	0.51	0.55
12	Sweetgum	1.99	0.46	0.52
13	Miscellaneous	5.33	0.53	0.59
Weighted average		100	0.528	0.590

[a] Moisture content is on dry basis.
[b] Freshly cut wood (no drying).

2.6.2 Wood density and specific gravity

Rough green lumber

In Table 2.2, a weighted-averaged green specific gravity of 0.528 was calculated on the basis of species distribution percentages determined from primary mill data and each individual species' specific gravity from secondary data found in *Hardwoods of North America* (Alden 1995). Using initial MC_{DB} = 85% and a weighted-averaged green specific gravity of 0.528, a density of 977 kg/m^3 was estimated for rough green lumber using table 4-6a in the *Wood Handbook* (Glass and Zelinka 2010).

Rough and planed dry lumber

In Table 2.2, a weighted-averaged 12% MC_{DB} specific gravity of 0.590 was calculated based on the species distribution percentages determined from primary mill data and each individual species' specific gravity from secondary data found in *Hardwoods of North America* (Alden 1995). Using a final MC_{DB} of 8% and a weighted-averaged 12% MC_{DB} specific gravity of 0.590, a density of 648 kg/m3 and specific gravity of 0.600 was estimated for rough and planed dry lumber using table 4-6a in the *Wood Handbook* (Glass and Zelinka 2010).

2.6.3 Wood fuel

Types

Distinguishing between different wood fuels is necessary when entering wood fuel values into SimaPro 7. Wood arrives at the mill gate either as part of the log or as purchased wood fuel. It is important to separate the two major types to track the environmental impact correctly. Several SimaPro 7 wood fuel processes were changed to correct for how the wood fuel arrived at the mill gate (Appendix B)

Moisture content

Wood FAL and wood into industrial boilers are based on average U.S. technology in the late 1990s (FAL 2003a, b) and uses green wood at 50% MC_{WB}. In accordance with CORRIM guidelines, wood fuel values were entered into SimaPro using OD weights with proper documentation of how this conversion was done for easier tracking. SimaPro emission data was given in SI units.

2.6.4 Wood residues

Green residue
Sprinkling usually affects only the MC of the bark, which can easily reach 60% to 70% and higher on a wet basis. Bark is typically mulched and sold by either the ton or cubic yard. For one mill, bark is also used as wood fuel and makes up 12.6% of total wood fuel consumed on-site on a weighted-average basis over all mills. Some mills grind up their bark into hog fuel.

Sawing logs produces green sawdust, green chips, green bark, and green hog fuel. Green chips were the greatest proportion of green wood residue at 22.0% by weight of the total log wood volume. Green hog fuel is next at 13.2% whereas green sawdust and green bark are 5.5% and 4.1%, respectively. For these materials except green bark, the weighted-average MC from the surveyed mills is 85% MC_{DB} whereas MC from green bark is 100% oven dry basis.
Dry (kiln dry) residue
The planing process produces two types of kiln dry residue: shavings and sawdust. Most of this material is used as on-site wood fuel. For this material, the weighted-average MC from surveyed mills is 8% MC_{DB}.

2.6.5 Lumber volume conversion factors

The purpose of developing conversion factors is to derive material and energy use based on 1.0 m^3 of planed dry lumber because dimensions vary when the lumber is processed. The different sizes of material from the sawmill, dryer, and planer were estimated based on data from the *Wood Handbook* (Bergman 2010). A rough green lumber conversion factor was assumed at 2.44 m^3/MBF. Volume shrinkage from rough green lumber to rough dry lumber was estimated at 12.7% from 30% to 8% based on species mix. Also, material loss from planing rough dry lumber is approximately 21%. Conversion factors of 2.13 and 1.68 m^3/MBF were also calculated for rough dry and planed dry lumber, respectively. The ratios show that for 1.0 m^3 of planed dry lumber, 1.45 m^3 of rough green lumber and 1.27 m^3 of rough dry lumber were used.

For example, wood fuel consumption was based on the actual rough green lumber entering and rough dry lumber exiting the drying process. After the wood fuel values were found for drying based on the rough dry lumber produced on a board foot basis, the energy values were then converted to a per unit basis of planed dry lumber basis using values given above.

3.0 Product Yields

Mass and energy values, including emissions for hardwood lumber production, were obtained by surveying 12 mills in the SE United States that provided detailed data on mass flow and energy consumption and type of fuel. Survey data were modeled in SimaPro 7 to find non-wood raw material use and emission data. Input data collected by survey are provided in Appendixes C-1 through C-5.

Weighted-averaged annual production for the hardwood sawmills was 76.4 thousand m^3 (31.3 million bf[2]) with a range of 17.4 to 131 thousand m^3 (7.1 to 53.7 million bf). For the NE/NC United States, a large production hardwood lumber mill is considered 30.8 thousand m^3 (12 million bf[5]) or more (Bergman and Bowe 2008). Regarding mill participation, it was important that the HMA supported the project so that sufficient production data could be obtained to meet the minimum CORRIM requirement of 5% of total production in the SE region.

[5] 2.57 m^3/MBF rough green hardwood lumber (Bergman and Bowe 2008)

Weighted-averaged mill features were a log diameter of 396 mm (15.6 in.) and production kiln capacity of 1.00 thousand m^3 (425 thousand bf[6]). Also, pulp chips were the largest proportion of wood residue produced at 284 OD kg/m^3 planed dry lumber (Table 3.1). The species sawn were red and white oak (over half), hard and soft maple, yellow poplar, cottonwood, ash, sweetgum, pecan, hickory, hackberry, bald cypress, and some miscellaneous species.

Table 3.1. Weighted-averaged wood mass balance (OD kg per m3 planed dry lumber)

	Sawing process		Internal process input	Boiler process input	Drying process		Planer process		All processes combined		
Material	**Input**	**Output**			**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Difference**
Green logs[a]	1,290								1,290	0	–1290
Green logs[b]	53								53	0	–53
Green chips		284	33						33	284	251
Green sawdust		71		29					29	71	42
Green bark		53		26					26	53	27
Green hog fuel		170		42					42	170	128
Rough green lumber		765			765				765	765	0
Rough dry lumber						765	765		765	765	0
Planed dry lumber								600	0	600	600
Dry shavings				77				119	77	119	42
Dry sawdust				32				46	32	46	14
Total	1,343	1,343	33	206	765	765	765	765	3,112	2,873	–239

[a]Log wood volume only.
[b]Log bark volume.

For the mass balance, the LCI study examined the four main unit processes and the overall process to track material flow. Using a weighted-averaged approach, 1290 OD kg (2,840 OD lb) of incoming hardwood logs with a density of 977 kg/m^3 (61.0 lb/ft^3) produced 1.0 m^3 (595 nominal bf) of planed dry lumber. Sawing produced 765 kg of rough green lumber; the drying process did not result in any loss of wood substance. Planing reduced the 765 OD kg of rough dry lumber to 600 OD kg of planed dry lumber, for a 21% reduction in mass. Boilers burned 206 OD kg of both green and dry wood fuel produced on-site (Table 3.1). Overall, an average log was reduced to 46.5% of its original mass in conversion to the final product of planed dry lumber. A percentage difference of 1% was calculated based on the overall mass balance that included intermediate products such as rough green and rough dry lumber. Appendix D-1 and D-2 provide flowcharts showing weighted-averaged material flow including co-products (excluding intermediate products) and showing an overall wood balance including intermediate products.

Most mills in the United States use volumetric values such as board feet log scale to purchase and a lumber tally for selling and therefore need to track log breakdown to find mill efficiency. The lumber recovery factor (LRF) is one way to track the log breakdown. LRF quantifies productivity as the nominal board feet lumber tally recovered per cubic foot of log inputs. In the SE region of the United States, 2.44 m^3 (86.2 ft^3) of hardwood logs are sawn, dried, and planed into the final product of 1.0 m^3 (595 nominal bf) of planed dry lumber, for a total volume conversion of 41.0% of incoming logs (Table 3.2). The difference for total volume and total mass conversion was due to lumber shrinkage during the drying process (Table 3.3).

[6] 2.36 m^3/MBF

Table 3.2. Volume conversion of incoming logs to 1.0 cubic meter of planed dry lumber

	Wood volume (actual dimensions)[a]		
	(m^3/m^3)	(ft^3/MBF)[b]	(%)
Raw wood material			
Incoming green log	2.44	145	100
Intermediate products			
Rough green lumber	1.45	86.0	59.4
Rough dried lumber	1.27	75.3	52.0
Final product			
Planed dried lumber	1.00	59.3	41.0

[a]All values provided in actual dimensions.
[b]1.68 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber.

Table 3.3. Mass conversion of incoming logs to planed dry lumber (oven dry weights)

	SI units (per m^3)		English units (per MBF[b])	
Material	**In**	**Out**	**In**	**Out**
Logs[a]	2.44 m^3		145 ft^3	
Green chips, sold	—	251 kg	—	920 lb
Green chips, internal use	—	32.9 kg	—	122 lb
Green sawdust, sold	—	42.3 kg	—	149 lb
Green sawdust, fuel	—	29.0 kg	—	102 lb
Green hog fuel, sold	—	128 kg	—	450 lb
Green hog fuel, fuel	—	25.9 kg	—	91.4 lb
Bark, mulch	—	26.8 kg	—	94.6 lb
Bark, fuel	—	25.9 kg	—	91.4 lb
Rough green lumber	—	1.45 m^3	—	1 MBF (2.44 m^3)
Rough dry lumber	—	1.27 m^3	—	1 MBF (2.13 m^3)
Dry shavings, sold	—	41.6 kg	—	147 lb
Dry shavings, fuel	—	77.4 kg	—	273 lb
Dry sawdust, sold	—	14.0 kg	—	49.4 lb
Dry sawdust, fuel	—	31.4 kg	—	111 lb
Planed dry lumber	—	1.0 m^3	—	1 MBF (1.68 m^3)

[a]Bark not included in green log volume.
[b]Conversion is 1.68 m^3 per MBF.

4.0 Energy Consumption

4.1 Total

Hardwood lumber production requires both electrical and thermal energy for processing logs into planed dry lumber. All the thermal energy is produced on-site, whereas most electricity is produced off-site from a regional power grid. Electrical energy is required for sawing, drying, and planing processes, whereas most of the thermal energy is required for the drying process. All but one mill reported their electrical usage. Total electrical consumption was 632 MJ/m^3 (295 kWh/MBF) of planed dry lumber. Of this total, 5,167 MJ of process energy (unallocated) consumed per cubic meter planed dry lumber, 4,678 MJ was for drying; 334 MJ for on-site electrical generation (co-generation); and 155 MJ for plant heat. This includes both off-site and on-site electrical sources (Table 4.1).

Table 4.1. Material and energy consumed on-site to produce 1.0 m3 of planed dry lumber (SimaPro input values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

Fuel type	Quantity (Units/m^3)	(Units/MBF[e])
Fossil fuel[a]		
Natural gas	3.5 m^3	0.21 1000 ft^3
Fuel oil #6	0.49 L	0.22 gal
Propane	1.46 L	0.65 gal
Electricity[b]		
Off-site generation	598 MJ	279 kWh
On-site generation	33 MJ	16 kWh
On-site transportation fuel[c]		
Off-road diesel	4.23 L	1.88 gal
Gasoline	0.44 L	0.19 gal
Propane	0.04 L	0.02 gal
Renewable fuel[d]		
On-site wood fuel	206 OD kg	764 OD lb
Purchased wood fuel	31.7 OD kg	117 OD lb
Water use		
Surface water	25.4 L	11.3 gal
Ground water	217 L	96.6 gal

[a]Energy values were determined using their higher heating values (HHV) in MJ/kg: 43.3 for fuel oil #1 and #2.

[b]Conversion unit for electricity is 3.6 MJ/kWh.

[c]Energy values were determined using their higher heating values (HHV) in MJ/kg: 45.5 for off-road diesel and 54.4 for gasoline.

[d]Values given in oven-dry weights (20.9 MJ/OD kg).

[e]1.68 actual m^3 per 1.0 nominal MBF planed dry lumber.

Table 4.2 shows the allocated cumulative energy of making 1.0 m^3 of planed dry lumber. For cumulative energy allocated to planed dry lumber, a value of 5,860 MJ/m^3 was found. Wood Fuel/Wood Waste provides by far the largest portion of energy needed and most of this because of the intensive energy for kiln drying the lumber.

Table 4.2. Cumulative energy (HHV) consumed during production of planed (surfaced) dry hardwood lumber—cumulative, allocated gate-to-gate LCI values (SimaPro output values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

Fuel[a,b]	Southeast lumber		
	(kg/m^3)	(MJ/m^3)	BTU/MMBF[c,d,e]
Wood fuel/wood waste[f]	184 kg	3,858	6,151,00
Coal	31.4 kg	823	1,312,000
Natural gas	6.90 kg	375	599,000
Crude oil	7.64 kg	348	555,000
Hydro	0	19	30,000
Uranium	0.00112 kg	427	681,000
Energy, unspecified	0	10	17,000
Total		5,860	9,345,000

[a]Values are allocated and cumulative and based on HHV.

[b]Energy values were found using their higher heating values (HHV) in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.

[c]1.68 m^3 per 1.0 nominal MBF.

[d]Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

[e]Conversion for units of energy is 948.8 BTU/MJ.

[f]Values given in oven-dry weights

4.2 Electrical Energy Composition for Unit Processes

For the following unit processes, sawing, drying, and planing, the distribution of electrical energy consumption was 50%, 25%, and 25% of the total, respectively. Based on these percentages, the three unit processes use 299, 149.5, and 149.5 MJ/m^3, or 140, 70, and 70 kWh/MBF planed dry lumber, respectively. Wood-fuel cogeneration provides 5.3% of total electricity consumed.

4.3 Sources of Energy

4.3.1 Major sources

The process energy required for drying and other associated drying processes (including cogeneration) and facility heating is based on fuel consumption with the major source being wood fuel produced on-site from the sawing process. A portion of wood fuel produced on-site, 206 OD kg, and some purchased wood fuel, 31.7 OD kg, is combusted to generate heat for the mill per 1.0 m^3 planed dry lumber. Thermal energy produced on-site is the largest proportion of energy used on-site. Overall, wood fuel contributed 96% to total energy produced on-site, with natural gas at 2.6%. In addition, grid electricity is a major factor in determining environmental impact, and this electricity was produced off-site (beyond the mill’s boundary) for use on-site in the manufacturing process. Coal was the largest fuel source for grid electricity—most grid electricity is from coal power plants in the SE United States.

4.3.2 On-site transportation fuel

On-site transportation of wood stock is a major fuel consumer, with off-road diesel having the highest consumption. On-site transportation includes forklifts, front-end loaders, trucks, and other equipment used within the system boundary of the facility. Off-road diesel consumption is 4.23 L/m^3 of planed dry lumber and is consumed at nearly 9 times the rate of propane and gasoline combined, on average. Transportation fuel consumption for the unit processes is 40%, 20%, 20%, and 20% for log yard operations, sawing, drying, and planing, respectively. Corresponding values of the four unit processes for off-road diesel are 1.69, 0.846, 0.846, and 0.846 L; for propane, 0.175, 0.088, 0.088, and 0.088 L, respectively.

4.3.3. Off-site electricity

Off-site generation of electrical power affects the environmental impact because of all the different fuels used to generate power. Average composition of (off-site) electrical generation was found for the SE region by totaling the amount of different fuel sources for each of the eight states given in thousand kilowatt hours and calculating the percentages (USDOE 2009). The most significant electric power contributor in the SE region is coal, with 51.1% of total electrical utility power being provided by this fuel source. Other fuel sources are nuclear, natural gas, petroleum, hydro, and other renewables, which provide 28.4%, 12.8%, 1.2%, 2.5%, and 1.9%, respectively (Appendix E-1).

5.0 Water Consumption

Water use was mainly for sprinkling logs, dust control, and boiler make-up water. Nine mills used water sprinklers and four mills used pond storage to wet logs to prevent staining. Of the 12 mills, two mills used both types of wetting logs and one mill did not wet their logs. Water consumption was based on responses from six mills, with one mill using nearly 70% of total reported consumption mostly for sprinkling logs. Dust control is a problem for several mills having air yards surfaced with gravel, especially during the dry season. Some mills are actively examining alternative methods. A surface and ground water consumption of 25.4 and 217 L/m^3 (11.3 and 96.6 gal/MBF) of planed dry lumber was calculated, respectively.

6.0 Transportation Distance

6.1 Logs

Logging transportation data were required to connect the forest resource LCI to the hardwood lumber LCI. An average one-way haul distance for hardwood log (including bark) transportation of 60.4 km (37.5 miles) with 100% empty backhaul was calculated from primary mill data. Mill average log MC was 45.9% wet basis (85% MC dry basis).

6.2 Purchased wood fuel

All purchased wood fuel was brought to one mill for heating the dry kilns and for operating a cogeneration unit. A cogeneration unit provides both thermal and electrical energy for use on-site. An average one-way haul distance for purchased wood fuel transportation of 3.64 km (2.26 miles) with 100% empty backhaul was calculated from primary mill data. Mill average purchased wood fuel MC was 7.4% wet basis (8% MC dry basis).

7.0 Environmental Impact

SimaPro 7 modeled output factors during the manufacturing process with major consumption for raw materials, other than wood, for electrical generation. Major uses of raw material, other than logs processed into lumber, were purchased wood fuel (waste), coal, crude oil, natural gas, and limestone, with allocated values of 24.6, 31.4, 7.64, 6.90, and 4.92 kg, respectively. A wood volume of 1.27 m^3 entered the planing process to produce 1.0 m^3 planed dry lumber (Table 7.1). Limestone and most of the coal were used to produce off-site electricity, and oil and natural gas was for both off-site electricity and thermal energy used on-site. Limestone helps remove sulfur dioxide emitted from burning coal. The region selected for production affects the environmental impact of hardwood lumber production because coal is the primary off-site material used for electrical power production in the SE, whereas most power in the Pacific Northwest is produced from hydro and natural gas.

Table 7.1. Raw materials consumed during production of planed (surfaced) dry lumber—cumulative, allocated gate-to-gate LCI values (SimaPro output values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

Raw material[a]	**Quantity**[b] (Units/m^3)	**Quantity**[b] (Units/MBF)[c]
Logs at mill gate[d]	1.27 m^3	75.3 ft^3
Water, well, in ground[e]	0.126 m^3	7.45 ft^3
Water, process and cooling, surface[e]	0.014 m^3	0.86 ft^3
Purchased wood waste [g]	24.6 kg	91.2 lb
Coal, in ground[e]	31.4 kg	116 lb
Gas, natural, in ground[e]	6.90 kg	25.6 lb
Oil, crude, in ground[e]	7.64 kg	28.3 lb
Limestone, in ground[e]	4.92 kg	18.2 lb
Energy, from hydro power[f]	18.5 MJ	8.65 kWh
Energy, unspecified[f]	10.3 MJ	4.83 kWh
Uranium, in ground[e]	0.00112 kg	0.00394 lb

[a] Values are allocated and cumulative.

[b] Energy values were found using their higher heating values (HHV) in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium.

[c] 1.68 m^3 per 1.0 nominal MBF.

[d] Amount of wood in lumber form entering the planing process; no shrinkage taken into account from drying process.

[e] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

[f] Conversion for units of electricity is 3.6 MJ/kWh.

[g] Values given in oven-dry weights

Two different life-cycle inventory scenarios for manufacturing hardwood lumber were evaluated based on the 12 mills surveyed: allocated cumulative and allocated on-site. The method for evaluating the two scenarios followed the ISO 14040 standards and SimaPro provided the results. The allocated accumulative scheme examined all emissions for electricity and thermal energy generation that were required to produce 1.0 m^3 of planed dry lumber starting with hardwood logs at the mill gate. These emissions involve the cradle-to-gate resource requirements (production and delivery) of grid electricity, fossil fuels, purchased wood fuel used in the boiler, and fossil fuels used in yard equipment such as forklifts. Also, emission data for on-site combustions of the two latter materials and wood fuel generated on-site were included. Transportation of logs (including bark) to the mill gate was included in the first scenario. The allocated on-site scheme only includes emissions from the combustion of all fuels used at the mill, therefore it did not involve the manufacturing and delivery of material and electricity consumed at the mill.

Table 7.2 shows the lower environmental impact of on-site compared to accumulative emissions for the 12 mills surveyed. Carbon dioxide and particulates are typically measured, although other emissions are frequently monitored from boilers to ensure regulatory compliance. Carbon dioxide (CO_2) emissions are separated by two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil-fuel-derived).

Biogenic CO_2 is considered carbon neutral because the CO_2 emitted is reabsorbed during the growth of the tree and released upon the decomposition or burning of the tree. Accumulative total emission values of 424 and 131 kg were reported from SimaPro for CO_2 (biogenic) and CO_2 (fossil), respectively (Table 7.2). The percentage of biogenic CO_2 to total CO_2 increased from 76.4% to 91.5% from the total to on-site schemes. Volatile organic compound (VOC) gases produced from drying lumber generated the value of 0.043 kg (0.159 lb/MBF) regardless of scenario. An overall value of 0.050 kg/m^3 rough green lumber was calculated from literature (Rice and Erich 2006, Rice 2008).

Table 7.2. Life-cycle inventory results for total emissions on a per unit basis of planed dry lumber

	Allocated total		**Allocated on-site**	
SUBSTANCE	**(kg/m^3)**	**(lb/MBF)[a]**	**(kg/m^3)**	**(lb/MBF)[a]**
Water emissions				
Biological oxygen demand (BOD)	4.98E-04	1.85E-03	3.78E-07	1.40E-06
Cl^-	1.96E-02	7.25E-02	1.78E-05	6.58E-05
Suspended solids	5.33E-02	1.98E-01	2.09E-04	7.74E-04
Oils	7.71E-03	2.86E-03	—	—
Dissolved solids	4.27E-01	1.58E+00	6.35E-05	2.35E-04
Chemical oxygen demand (COD)	5.25E-03	1.95E-03	3.24E-05	1.20E-04
Soil emissions				
Waste in inert landfill	0.50	1.87	0.50	1.87
Waste to recycling	0.207	0.765	0.207	0.767
Solid waste	33.2	123	18.2	67.4
Air emissions				
Acetaldehyde	6.05E-04	2.24E-03	6.07E-04	2.25E-03
Acrolein	1.12E-06	4.15E-06	—	—
Benzene	7.27E-04	2.69E-03	7.28E-04	2.70E-03
CO	3.57	13.2	3.43	12.71
CO_2 (biomass)	424	1,569	425	1,573
CO_2 (fossil)	131	485	39.4	146
CH_4	1.97E-01	7.31E-01	1.94E-04	7.18E-04
Formaldehyde	1.12E-02	4.15E-02	1.12E-02	4.16E-02
Mercury	2.41E-06	8.92E-06	2.46E-07	9.11E-07
NOx	1.37	5.08	0.95	3.54
Non-methane, volatile organic compounds (NMVOC)	2.05E-01	7.58E-01	6.82E-02	2.53E-01
Particulate (PM10)	1.12E-01	4.15E-01	8.25E-02	3.06E-01
Particulate (unspecified)	7.99E-02	2.96E-01	—	—
Phenol	8.07E-03	2.99E-02	8.09E-03	3.00E-02
Sox	0.85	3.14	0.10	0.38
VOC	0.043	0.16	0.043	0.16

[a] 1.68 m^3 per 1.0 nominal MBF planed dry lumber.

Material and energy resources consumed to manufacture 1 m^3 of planed dry hardwood lumber are shown in Table 4.1. These LCI input values are unallocated and were input into SimaPro 7 to find the environmental burdens of manufacturing 1 m^3 of planed dry hardwood lumber. Table 7.3 gives on-site energy values unallocated and allocated to the planed dry lumber. Unallocated values were calculated from material and energy resources found in Table 4.1 were the sum of all fuel and electricity inputs to the process. Allocated on-site energy use is roughly 75% of the total unallocated on-site use. Material and energy consumed at the mill for SimaPro 7 gave LCI outputs allocated to manufacturing dry planed lumber only, not to associated wood co-products. Some LCI outputs listed raw materials used.

Table 7.3. Fuel and electrical energy used to produce a cubic meter of planed dry lumber

	Energy use at mill	
	Unallocated (MJ/m3)	**Allocated (MJ/m3)**
Fossil fuel[a]		
Natural gas	1.36E+02	1.06E+02
Fuel oil #6	2.06E+01	1.60E+01
Propane	3.87E+01	3.01E+01
Electricity[b]		
Off-site generation	5.98E+02	4.65E+02
On-site generation	3.34E+01	2.60E+01
On-site transportation fuel[c]		
Off-road diesel	1.64E+02	6.71E+01
Gasoline	1.53E+01	6.25E+00
Propane	9.42E-01	3.86E-01
Renewable fuel[d]		
On-site wood fuel	4.32E+03	3.36E+03
Purchased wood fuel	6.62E+02	5.14E+02
Total	**5.99E+03**	**4.48E+03**

[a]Energy values were determined using their higher heating values in MJ/kg: 43.3 for fuel oil #1 and #2.

[b]Conversion unit for electricity is 3.6 MJ/kWh.

[c]Energy values were determined using their higher heating values in MJ/l: 38.7 for off-road diesel, 26.6 for propane, and 34.8 for gasoline.

[d]Values given in oven-dried weights (20.9 MJ/OD kg).

8.0 Carbon Balance

Carbon emissions are playing an increasingly important role in policy decision making in the United States and throughout the world. The impact of carbon was determined by estimating values of carbon found in wood and bark as described from previous studies, such as Skog and Nicholson (1998), using a mixture of hardwood roundwood values for the SE United States. We used a mixed hardwood factor of 317.5 kg/m^3 of wood material and a carbon content of 52.9% with an incoming log wood mass of 1290 OD kg/m^3 planed dry lumber to calculate the carbon balance. Total carbon input and output of 837 and 846 kg/m^3 planed dry lumber were found (Table 8.1) resulting in a difference of 1.0%. Contribution to the carbon balance from air emissions are shown in Table 8.2. A cubic meter of planed dry hardwood lumber stores 1,164 kg CO_2-equivalents as a final product.[7]

[7] Multiplying (mass of hardwood lumber) × (carbon content) × (carbon to carbon dioxide conversion) = 600kg × 52.9% * 44/12 = 1,164 kg CO_2 equivalents.

Table 8.1. Tracking of wood-based carbon inputs and outputs for SE hardwood lumber

	Elemental carbon	
Substance[a]	**(kg/m^3)**	**(lb/MBF)**[b]
Input		
Logs	683	2,526
Bark	28	103
Wood fuel[c]	126	467
Sum carbon in	837	3,096
Output		
Planed dry lumber	318	1,118
Co-products[c]	393	1,384
Solid emissions	18	62
Air emissions	117	414
Sum carbon out	**846**	**2,978**

[a]Wood-related carbon and its emissions.

[b]1.68 m^3 per 1.0 nominal MBF (thousand board feet) planed dry lumber.

[c]Bark leaves system both as wood fuel and as a co-product (mulch).

Table 8.2. Composition of wood-based air emissions related to carbon contribution

	Total[a]		Carbon[a]		
Substance	**(kg/m^3)**	**(lb/MBF)**[b]	**(%)**[c]	**(kg/m^3)**	**(lb/MBF)**[b]
Benzene	7.27E-04	2.69E-03	92.3	6.71E-04	2.48E-03
Carbon dioxide, biogenic	4.24E+02	1.57E+03	27.3	1.16E+02	4.28E+02
Carbon monoxide	3.57E+00	1.32E+01	42.9	1.53E+00	5.66E+00
Formaldehyde	1.12E-02	4.15E-02	40.0	4.48E-03	1.66E-02
Methane	1.97E-01	7.31E-01	75.0	1.48E-01	5.48E-01
Naphthalene	4.84E-04	1.79E-03	93.7	4.54E-04	1.68E-03
NMVOC, non-methane volatile organic compounds, unspecified origin	2.05E-01	7.58E-01	88.2	1.80E-01	6.68E-01
Organic substances, unspecified	8.16E-02	3.02E-01	50.0	4.08E-02	1.51E-01
Phenol	8.07E-03	2.99E-02	76.6	6.18E-03	2.29E-02
VOC, volatile organic compounds	4.29E-02	1.59E-01	88.2	3.79E-02	1.40E-01
Total	**428**	**1,584**	**27.5**	**117.5**	**435**

[a]All values per unit of planed dry lumber.

[b]1.68 m^3 per 1.0 nominal MBF planed dry lumber.

[c]Percentage from Softwood Lumber LCI (Milota et al. 2004) and Softwood Plywood LCI (Wilson and Sakimoto 2004).

9.0 Sensitivity Analysis

A sensitivity analysis was completed per ISO 14040 standards and SimaPro to model the effects of using different quantities of fuel sources for thermal energy generation. Sensitivity analysis can be useful to understand how various process parameters contribute to environmental output factors. For instance, in hardwood lumber manufacturing, heat is used in several sub-processes, consuming a combination of wood, natural gas, and fuel oil as fuel to generate the heat. Changing fuel sources, also referred to as fuel switching, can have a significant effect on the type and quantity of emissions. This sensitivity analysis compared the effects of the "base" fuel mix to using (1) all on-site generated wood fuel (mostly dry shavings from the planing process and green hog fuel from the sawing process) and (2) using all natural gas as a fuel input. Natural gas is chosen because it burns cleaner than fuel oil and is abundantly available domestically.

9.1 Alternative Fuel Sources

The "base" fuel mix in this study included four fuel sources, with wood fuel and natural gas supplying the majority of the energy. Propane and fuel oil contributed 1.1%. Based on survey data, the original model assumed that 96.2% of the fuel used was in the form of wood fuel (83.4% produced on-site and the remainder purchased) and 2.6% as natural gas. Most mills use only one or two types of fuel, whereas the original study resulted in a weighted-averaged composite model incorporating different fuel sources taken from primary mill data for 12 mills. In this sensitivity analysis, two alternative fuel-use schemes were created for comparison to the "composite mill" or "base" scenario. One alternative assumed consumption of only on-site (generated) wood fuel used for all thermal energy by increasing the initial base value of 206 to 247 OD kg for this "100% on-site wood fuel" case to generate 5,167 MJ/m^3 (8.24 million Btu/MBF) of planed dry lumber. The second alternative fuel-use scheme, "100% natural," had natural gas use increase from the base value of 3.5 to 136 m^3 to provide all necessary heat for the facility.

9.2 Three Fuel Source Scenarios

This sensitivity analysis examined three scenarios for heat generation using the base fuel mix, 100% natural gas, and 100% on-site (generated) wood fuel cases. The following three scenarios were modeled using SimaPro to find the differences in emissions: (1) comparing 100% natural gas case to the "base" hardwood lumber fuel mix that used both natural gas and wood fuel, (2) comparing 100% on-site (generated) wood fuel to the "base" hardwood lumber fuel mix that again had no fuel changes, and (3) comparing 100% natural gas to 100% on-site (generated) wood fuel cases.

9.3 Sensitivity Analysis Results

Table 9.1 presents the summary of the three fuel use scenarios, with a partial list of air emissions for the SE region. In scenarios 1 and 2, a negative percentage difference number indicated that the alternative fuel source released fewer emissions than did the base model. A positive percentage difference means that the base or original model released fewer emissions. Scenario 1 indicated that less particulate (PM10), acetaldehyde, and biogenic CO_2, but more fossil CO_2, methane, non-methane VOC, and SOx, were produced when burning 100% natural gas than in the base fuel mix (original). Scenario 2 showed more biogenic CO_2, both types of particulate, acetaldehyde, benzene, naphthalene, and phenol, but less fossil CO_2, and non-methane VOC were produced when burning 100% wood fuel than in the base fuel mix (original). In scenario 3, a negative number indicates that the all natural gas case released fewer emissions than the all on-site produced wood fuel case and a positive percentage number means that all on-site produced wood fuel model released fewer emissions. Scenario 3 highlighted the increase of fossil CO_2, non-methane VOC, and SOx produced along with less particulate (PM10) and biogenic CO_2 produced compared with scenario 1. For all three scenarios, the amount of VOC produced was similar regardless of the fuel used because most VOC originated in the actual drying of the hardwood lumber.

Table 9.1. Sensitivity analysis for manufacturing hardwood lumber in the Southeast

	Fuel distribution (kg/m^3 planed dry lumber)			Difference (%)		
Substance	100% natural gas	100% wood fuel[a]	Original (base)	Scenario 1 100% natural gas to original	Scenario 2 100% wood fuel to original	Scenario 3 100% natural gas to 100% wood fuel
Acetaldehyde	0.00E+00	6.41E-04	6.05E-04	–200.0	19.5	–200.0
Benzene	1.00E-06	7.70E-04	7.27E-04	–199.3	19.4	–199.4
CO_2 (biogenic)	8.10E-02	4.49E+02	4.24E+02	–199.9	19.5	–199.9
CO_2 (fossil)	1.36E+02	1.27E+02	1.31E+02	101.1	–26.6	119.6
CO	1.06E+00	3.74E+00	3.57E+00	–167.9	17.9	–172.8
Formaldehyde	8.33E-03	1.16E-02	1.12E-02	–52.3	15.7	–66.7
Methane	7.93E-01	1.84E-01	1.97E-01	17.4	8.3	9.1
Naphthalene	1.24E-07	5.13E-04	4.84E-04	–199.9	19.5	–199.9
NOx	1.08E+00	1.39E+00	1.37E+00	0.6	1.2	–0.6
Non-methane, VOC	1.04E+00	1.78E-01	2.05E-01	126.0	–61.4	157.0
Organic substances, unspecified	3.87E-02	8.60E-02	8.16E-02	–151.9	17.7	–159.0
Particulate (PM10)	6.32E-02	1.14E-01	1.12E-01	–31.2	12.0	–42.8
Particulate (unspecified)	7.44E-02	8.19E-02	7.99E-02	14.1	8.3	5.8
Phenol	3.36E-06	8.55E-03	8.07E-03	–199.8	19.5	–199.8
SOx	3.91E+00	7.28E-01	8.48E-01	54.2	–1.7	55.7
VOC	3.93E-02	4.37E-02	4.29E-02	–4.2	5.4	–9.7

[a]All wood fuel used was generated on-site.

10.0 Study Summary

A rigorous material and energy balance was completed on 12 hardwood mills located in the southeastern United States. The results indicate that total energy consumption varied significantly, depending on the species sawn, size of mill, method of drying, and origin of electricity (on-site or grid). For hardwood lumber, weighted-averaged process energy (unallocated) of 5,167 MJ/m^3 of planed dry lumber (8.24 million Btu/MBF) was found with 4,678 MJ for drying, 334 MJ for on-site electrical generation (co-generation), and 155 MJ for plant heat. Total electrical energy consumption of 632 MJ/m^3 of planed dry lumber (295 kWh/MBF) was also determined, including on-site electrical generation. Process energy used varied considerably, depending on whether the mill ran a cogeneration unit. The cogeneration unit converted 334 MJ of thermal energy into 33.4 MJ of electrical energy. Also, the larger mills tended to use less energy per unit of planed dry lumber for drying than the smaller mills.

We learned a couple lessons from calculating cumulative energy (allocated) in making lumber. Table 10.1 shows the difference by region and type of lumber for cumulative energy (allocated). As expected due to longer drying times and denser material, making hardwood lumber consumes significantly larger amounts of energy than softwood lumber. In addition, a larger value of 6,388 MJ/m^3 in the Northeast/North Central region may be contributable to energy needed to heat facilities and kiln dry frozen lumber during the winter months.

Table 10.1 Cumulative energy (HHV) consumed during production of planed (surfaced) dry lumber from the Southeast compared to softwood lumber produced in the Southeast and hardwood lumber produced in the Northeast/North Central region—cumulative, allocated gate-to-gate LCI values (SimaPro output values). Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

	CORRIM Phase I[b]	**CORRIM Phase II[c]**	
	Southeast	**Northeast/ North Central**	**Southeast**
Fuel[a]	(values in MJ)	(values in MJ)	(values in MJ)
Wood fuel/wood waste	3,023	3,721	3,858
Coal	411	896	823
Natural gas	232	793	375
Crude oil	97	615	348
Hydro	4	11	19
Uranium	170	344	427
Energy, unspecified	8	8	10
Total	**3,945**	**6,388**	**5,860**

[a]Energy values were found using their higher heating values (HHV) in MJ/kg: 20.9 for wood oven-dry, 26.2 for coal, 54.4 for natural gas, 45.5 for crude oil, and 381,000 for uranium..

[b]CORRIM Phase I projects dealt with structural building materials in the Pacific Northwest and the Southeast (primary producing regions).

[c]CORRIM Phase II projects deal with structural building materials in the Northeast/North Central and Inland West and hardwood lumber in the East.

11.0 Discussion

Total energy consumption per cubic meter of planed (surfaced) dry hardwood lumber was found to be comparable to published data (Armstrong and Brock 1989, Breiner et al. 1987, Comstock 1975, Bergman and Bowe 2008). However, unlike previous studies, processes such as facility heating and cogeneration were examined because their energy use was significant.

Our data show that wood has two significant advantages over non-wood substitutes: wood is carbon neutral and carbon contained in the wood structure can be sequestered (captured and stored). Therefore, using wood as a fuel (energy resource) or in a finished wood product from hardwood lumber (material resource) could be considered a sustainable practice. Other non-wood products typically do not have the benefits of a carbon-neutral product to use both as a fuel and a finished product. Also, decreasing energy consumption would be of great benefit to the mills both in terms of its financial benefits (cost reduction) and environmental burden benefits, especially in sawing and drying.

There are several approaches to lowering energy consumption, and the mills that incorporate these methods would ultimately have significantly lower energy use or increase productivity. Using improved sawing practices such as the best opening face program (Harpole and Hallock 1977), improved lumber sizing, and thinner kerf saws have increased lumber yields while lowering electricity consumption. Most large mills are using these technologies. Curve sawing technology is another approach already standard practice in the softwood lumber industry (Bond and Araman 2008).

Another approach reduces thermal energy use. Several different drying methods including altered kiln schedules can be used depending on species, fuel costs, and wood residue use. Air drying lumber is one such method but has not been the preferred method of drying because of drying degrades and large quantity of drying stock required. One mill we surveyed did have an air yard. Drying degrade is a reduction in lumber quality caused by drying; greater control of the drying process typically reduces drying degrade. Maintaining a large lumber inventory for air drying reduces profits because it delays investment recovery. Air drying lumber has the least control among the different drying methods, resulting in the highest level of degrade, although it provides the lowest energy use of all drying methods (FPL 1999, Denig et al. 2000, Nebel et al. 2006).

This report was critically reviewed by Maureen Puettman (WoodLife) to ensure ISO 14040 compliancy.

12.0 Conclusions and Recommendations

Based on the results, the following conclusions are drawn and recommendations made:

Burning fuel for energy generates CO_2. Nearly all energy burned on-site for manufacturing hardwood lumber comes from woody biomass. Burning biomass for energy does not contribute to increasing atmospheric CO_2 provided forests are regrowing and reabsorbing the emitted CO_2.

The amount of carbon stored in hardwood lumber exceeds the fossil carbon emissions by a factor of 9. Therefore, as long as hardwood lumber and its carbon stay in products held in end uses the carbon stored will exceed the fossil carbon emitted in manufacturing.

Sawing consumes the greatest proportion of electricity in the manufacturing of hardwood lumber. Thus, installing optimization equipment would lower electrical consumption by reducing sawing errors. Accurately sized lumber through proper target sizing and lumber size quality control, along with curve sawing technology, proper saw design, and use of thinner kerf saws, improves lumber recovery. These features also reduce electrical consumption and the volume of green wood residue produced.

Drying consumes the highest proportion of fuel. In this study, wood fuel accounts for 96% of thermal energy used. Lowering overall energy consumption by upgrading or overhauling existing older and inefficient dry kiln facilities is indicated.

Increasing on-site wood fuel consumption would reduce fossil greenhouse gases but increase other gases, especially particulate emissions. Particulate matter can be captured prior to release to the atmosphere using commercially available technology but not without increased costs.

The region selected for production affects the environmental impact of this product because coal represents the greatest proportion of off-site material used for electrical power generation in the Southeast region. Most power in the Pacific Northwest is produced from hydro and then natural gas, whereas most power in the Southeast is produced from coal and uranium just as in the Northeast/North Central region.

Increasing the level of air drying lumber and percentage of air drying prior to kiln drying, especially for species where color is not a problem, would lower the amount of energy required for the drying process. Therefore, improving air drying methods would lower energy use while maintaining lumber quality and reducing the environmental impact of hardwood lumber.

Caution is required when using wood product LCI studies and the final LCA for comparison to non-wood products. It may be more important to know exactly how much material is needed for the same use instead of basing comparisons on a volume or mass basis. An example would be how much hardwood flooring would be needed compared with a carpet system with a sub-floor. Floors and carpets are measured in square feet and yards, respectively, in the United States. This study gives results based on a cubic meter; therefore, thickness of material is a critical dimension for consideration.

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Appendix A-1: Primary Mill Data Questionnaire: Introduction and Questionnaire.

Hardwood Sawmill Analysis Project

Thank you for giving me the opportunity to work with you on a project involving the long-term viability and profitability of the U.S. wood products industry. Results from this project will be a good marketing tool for the U.S. hardwood industry particularly the green building industry. A growing demand for building projects that use environmentally friendly and energy-efficient materials has spurred a green movement in the construction industry. An estimated $10 billion of "green buildings" are in the process of construction this year in the United States.

This research will test the theory that using wood in more applications that substitute for non-renewable products can substantially improve environmental performance, thus increasing the marketability of forest products. As you know, wood offers unique opportunities to store carbon in the forest, products, and substitution (avoided fossil fuel intensive products) while also supporting other ecological services such as clean water, clean air, habitat, and recreation.

Based on the Eastern Region (all states bordering as well as east of the Mississippi River), my final report will describe a gate-to-gate analysis of hardwood sawmills. The information collected will show the comparison of wood versus non-wood materials on an energy, economic, and environmental basis. Regarding the questionnaire, our primary focus is on overall mill information because this data is vital for precise and accurate results. Details harder to report will be requested later so I encourage you to call with specific questions.

Questions will be focused on annual production, energy use and generation, material inputs, and environmental emissions. We realize that you may not have all the information requested, but the data you are able to provide will be appreciated. **Strict confidentiality** will be maintained for all the companies that supply the data for this project. Please complete the following questionnaire by **December 29, 2006**.

Company Name: ______________________________

Mill Address: ______________________________

____

Contact Person: ______________________________

Position/Title: ______________________________

Telephone: ____________ **Fax:** ______________

Questions should be directed to:
Rick Bergman – Wood Drying Researcher
University of Wisconsin - Wood Products Program
120 Russell Labs
1630 Linden Dr
Madison, WI 53706
Phone (608) 231-9477 / FAX (608) 231-9303
rbergman@wisc.edu

This report is part of a larger initiative sponsored by Consortium for Research on Renewable Industrial Materials (CORRIM) to provide a database of information for quantifying the environmental impacts and economic costs of wood building materials through the stages of planting, growing, manufacturing, construction, operational use, and demolition.

Hardwood Sawmill Analysis

We have divided the mill into four unit processes. This division is like drawing a boundary around a part of the process. We want to find out everything that crosses the boundary. We would like to get information on total inputs and outputs from the mill first and then for each unit process where possible; please contact Rick Bergman @ (608) 231-9477 with any questions or concerns.
This questionnaire is divided into six parts.

- Part I deals with a basic description of the mill and its operations.
- Part II requests information on primary mill's total inputs and outputs for each of the following processes
  - Section A - Sawing (logyard and sawmill)
  - Section B - Drying
  - Section C - Planing (planing and packaging of lumber)
  - Section D - Energy generation

Within each of the last four parts, the questionnaire contains series of tables organized as follows:

Inputs
    Materials
    Energy (fuels and electricity)
    Water
Outputs,
    Products
    Air emissions
    Liquid emissions
    Solid waste
Emissions control equipment

Please complete the tables by either hand written or typing responses in the spaces provided. Provide as much detail as possible. Please contact Rick Bergman @ (608) 231-9477 if you have questions.

Space is provided throughout the questionnaire for any additional comments, clarifications or observations you might care to add.

Units are generally specified, but if you have other units that are easier to use, please cross off our units and add yours.

If you do not know the quantities at the level of detail requested, group by category. For example, provide a value for all hazardous air pollutants (HAPs) if the quantities of individual compounds are not known.

Thank you for the time and effort to fill in the blanks. Not all mills have everything on the list and it should be easier than it looks to complete.

PART I – Operation Overview

Reporting Year:	Starting Month:	Ending Month:

General Mill Information

1. Mill type (please check all that apply):

- ❑ Green lumber mill
- ❑ Dry lumber mill
- ❑ Cant / tie mill
- ❑ Pallet mill
- ❑ Other (specify)____________________

2. Rough Green Lumber Production

For reporting year __________ thousand board feet (BF)

Percent kiln dried__________ %

3. Which of the following does this mill have (check each one that applies)?

- ❑ log storage
  - ○ dry deck
  - ○ sprinkled deck
  - ○ pond
  - ○ other: _______________
- ❑ log handling
  - ○ log sorter/merchandizer
  - ○ debarker
- ❑ sawmill
  - ○ head rig(s) how many _____
  - ○ resaws, how many: ______
  - ○ edgers, how many: ______
  - ○ edger optimizer
  - ○ trimmer optimizer
  - ○ trimmer
  - ○ sorter, # bins: ______
  - ○ sticker stacker
- ❑ dryers
  - ○ predryer
  - ○ conventional steam (10-15 psig)
  - ○ high temperature steam
  - ○ direct-fired
  - ○ dehumidification
  - ○ transfer car system
  - ○ air drying yard
- ❑ boiler
  - ○ wood-fired boiler
  - ○ gas-fired boiler (natural or propane)
  - ○ oil-fired boiler
  - ○ cogeneration facility
  - ○ bag house
- ❑ planers
  - ○ planer
  - ○ in-line moisture meter
  - ○ grading station
  - ○ trimmer
  - ○ end paint/seal
- ❑ other mill equipment

PART II – Total Material and Energy Inputs and Outputs

TOTAL LOG/LUMBER INPUTS (Annual Production – see Block Diagram on page 6)

- Logs: ***What type of log scaling is used?*** ______________________

  1. Volume of incoming logs ______________________ thousand BF
  2. Volume sorted & sold to outside firms ______________________ thousand BF
  3. Volume of logs to sawmill (on-site) ______________________ thousand BF

- Rough Green Lumber
  4. Volume from on-site sawmill ______________________ thousand BF
  5. Volume purchased from outside firms ______________________ thousand BF
  6. Volume sorted & sold to outside firms ______________________ thousand BF
  7. Volume from predryers ______________________ thousand BF
  8. Volume from airyard ______________________ thousand BF
  9. Volume to dry kilns ______________________ thousand BF

- Rough Dry Lumber
  10. Volume kiln-dried on-site ______________________ thousand BF
  11. Volume purchased from outside firms ______________________ thousand BF
  12. Volume sorted & sold to outside firms ______________________ thousand BF
  13. Volume to planer ______________________ thousand BF

- Planed Dry Lumber
  14. Volume from planer ______________________ thousand BF
  15. Volume purchased from outside firms ______________________ thousand BF
  16. Volume sorted and sold to outside firms ______________________ thousand BF
  17. Volume used internally (on-site) ______________________ thousand BF

Please complete the following table showing the breakdown of the individual tree species and approximate sizes processed by your mill. If less than 2% of total, use category labeled "Other".

Species	% of total log input into sawmill
Total	100%

TOTAL (NON-TRANSPORTATION) FUEL USE (see Block Diagram on page 7)

- Wood
  1. On-site wood boiler fuel ____________ @ ______ %MC tons
  2. Purchased wood boiler fuel ____________ @ ______ %MC tons

- Fossil Fuel
  3. Natural Gas ____________________ thousand cubic feet (ft^3)
  4. Fuel oil #1(kerosene) ____________________ gallons
  5. Fuel oil #2 (heating oil) ____________________ gallons
  6. Fuel oil #6 ____________________ gallons
  7. Propane ____________________ gallons
  8. Other ____________________
  9. Electricity for entire facility ____________________ kilowatt-hours (kWh)

TOTAL WATER USE

- Water ____________________ gallons or ft^3

TOTAL WOOD CO-PRODUCT/BY-PRODUCT OUTPUT

For each co-product and by-product, please indicate the percentages of total production for the reporting period that are sold (shipped) to other users, used internally (either as fuel or other uses), landfill, or inventoried for future use. Select whatever category best fits your mill's situation. If zero, enter a dash (-).

Co-products and By-Products	Moisture Content	Sold (Shipped)	Used Internally (as fuel)	Used Internally (other uses)	Landfilled	Inventory	Total
	(%)	tons	tons	tons	tons	tons	tons
Chips, green							
Sawdust, green							
Bark, green							
Edging strips, green							
Sawdust, dry							
Shavings, dry							
Hogged material							
Other							

TOTAL INDUSTRIAL (SOLID) WASTE **(material requiring disposal outside of mill)**

Type	Tons/Pounds	Percent Landfilled
Fly Ash		
Bottom ash		
General refuse		
Recycled material		

TOTAL AIR EMISSIONS

Type	Amount (pounds)
Particulate	
PM10	
HAPs	
Others (SO_2, ROG[1], etc.)	

[1]Reactive Organic Gases (also referred to as Volatile Organic Compounds)

TOTAL TRANSPORTATION FUEL USE ON-SITE[2]

Type	Units
On-road diesel	Gallons
Off-road diesel	Gallons
Fuel Oil #6	Gallons
Propane	Gallons
Gasoline	Gallons
Other	

[2]Include all sources of energy such as fuels for yard equipment, forklifts, and carriers

TRANSPORTATION – LOGGING TRUCKS

Mileage logging/lumber trucks travel annually ______________miles
______________% One-way
______________% Empty backhaul

ENERGY GENERATION - BOILER FUEL USE

1. If present, please indicate the actual (not rated) production output of every process boiler:

Boiler	Size (BTU/hr, HP, or lbs/hr of steam[3])	Fuel type	Quantity (units)
#1			
#2			
#3			

[3]If known, list boiler steam pressure

2. If any wood boiler fuel used on-site is ***purchased from off-site sources***, please indicate the amounts by type in the spaces provided below. Otherwise ignore and go to next question. If zero, enter a dash (-). Please make sure you show the **units** of measure.

Boiler Fuel	**Quantity**	**Units** (enter %MC if known)
Shavings, dry		
Sawdust, dry		
Sawdust, green		
Bark, green		
Hogged fuel (mixed grindings)		
Chips, green		

3. If present, please indicate the cogeneration facility production output:

Electricity (kW or MW)	Process heat (BTU/hr)	Fuel type	% used or sold off site	
			electricity	process heat

EMISSIONS CONTROL EQUIPMENT (ECD)

Include emission control devices (ECD) if any for air emissions such as cyclones, baghouses, and electric static precipitators (ESPs)

For water emissions, explain how runoff or other water discharges from the boiler and logyard are controlled (i.e. handled) such as settling pond, city sewer, septic

		Boiler #1	Boiler #2	Boiler #3	Sawmill	Planermill	Logyard
Type of Device							
Equipment controlled							
Electrical	[1]Usage, kWh						
	included in energy table, Y or N						
Type of emissions controlled							

[1]Or state other units

Glossary

Product = the primary material produced from manufacturing and "sold outside of the system boundary;"
Co-product = a material produced from manufacturing and "sold outside of the system boundary;"
Internal by-product = a material produced during the manufacturing that is recycled or used "within the system boundaries"
Industrial waste = a material produced during the manufacturing that requires "disposal outside of the system boundary"
HAPs = Hazardous Air Pollutants
ROG = Reactive Organic Gases (also referred to as Volatile Organic Compounds (VOCs)
Slabs = the lumber cut on a circular or band head rigs from the outside portions of logs when squaring the log for lumber; does not have square edges
Edgings = these pieces of board that passed through a machine called an edger that can make two or more lineal cuts simultaneously
General refuse = waste collected from the sawmill operation that is mixed with dirt and cannot be sent to the boiler
Recycled material = material collected from the sawmill operation that is recycled
Packaging material = steel strapping, plastic lumber covers, and cardboard corners

Appendix A-2: Primary Mill Data Questionnaire:
Explanation and Diagrams

PART A – SAWING

Reporting Year:	Starting Month:	Ending Month:

Description of Unit Process

This unit process begins with logs in the mill yard and includes:

- in-yard transportation of logs from the point of unloading to the deck;
- sorting and storage of logs;
- in-yard transportation of logs from the deck to the optimizer or debarker;
- cutting to length of logs or tree lengths;
- debarking of the logs;
- breakdown of logs into rough lumber, pulp chips, bark, slabs, edgings, and sawdust;
    - slab is the lumber cut on a circular or band head rigs from the outside portions of logs when squaring the log for lumber; does not have square edges
    - edgings are these pieces of board that passed through a machine called an edger that can make two or more lineal cuts simultaneously
- stacking, stickering, and in-yard transportation of rough lumber to kilns or planar facilities;
- sawfiling and maintenance of all sawmill equipment and yard transportation vehicles; and
- treatment of process air, liquids, and solids.

The outputs of this unit process are rough green lumber, chips, bark, slabs, edgings, and sawdust.

PART B – DRYING

Reporting Year:	Starting Month:	Ending Month:

Description of Unit Process

This unit process begins with rough green lumber and includes:

- loading of stickered lumber into a kiln facility;
- heat treatment, drying, equalizing and conditioning of lumber within the kiln;
- maintenance of all kiln equipment and related yard transportation vehicles;
- treatment of process air, liquids and solids; and
- unloading and transportation of kiln-dried lumber to the planar mill.

The output of this unit process is stickered, rough kiln-dry lumber delivered to the planar mill.

PART C – PLANING

Reporting Year:	Starting Month:	Ending Month:

Description of Unit Process

This unit process begins with either rough green lumber or stickered, rough kiln-dried lumber.

The operations associated with this unit process include:

- de-stickering and/or unstacking of lumber;
- planing (surfacing) of lumber;
- trimming, grading, and sorting of lumber;
- stacking, strapping, and packaging of lumber.
- transportation of lumber within the planer operation and loading for shipping
- maintenance of all planar equipment and associated yard transportation vehicles; and
- treatment of process air, liquids and solids.

The output of this unit process is surfaced and packaged lumber, sorted by type, size and grade as well as planar shavings, sawdust, pulp chips, and/or lumber trim ends.

PART D – ENERGY GENERATION (BOILER)

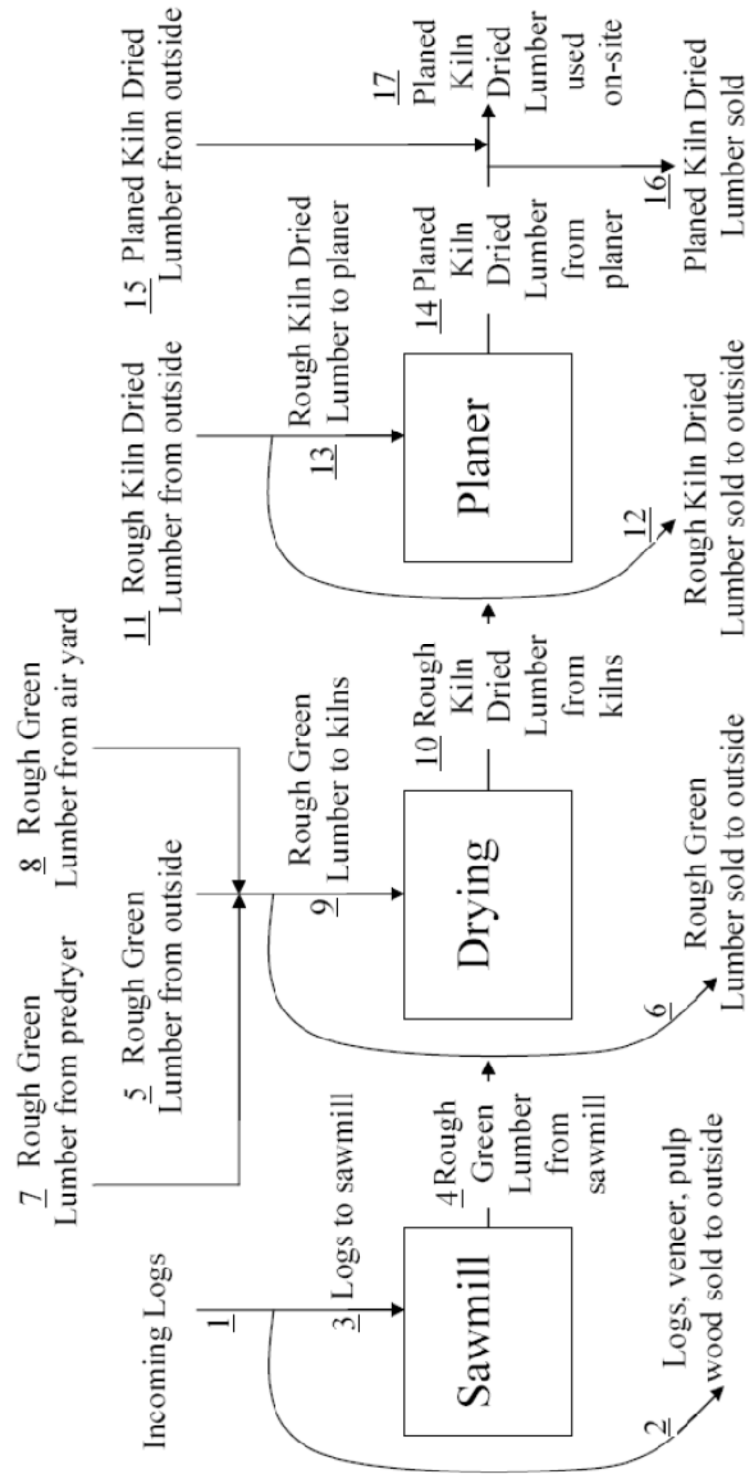
Reporting Year:	Starting Month:	Ending Month:

Description of Unit Process

This unit process provides heat and in some cases electricity for use in other parts of the mill or to be sold. A fuel such as wood or natural gas is burned.

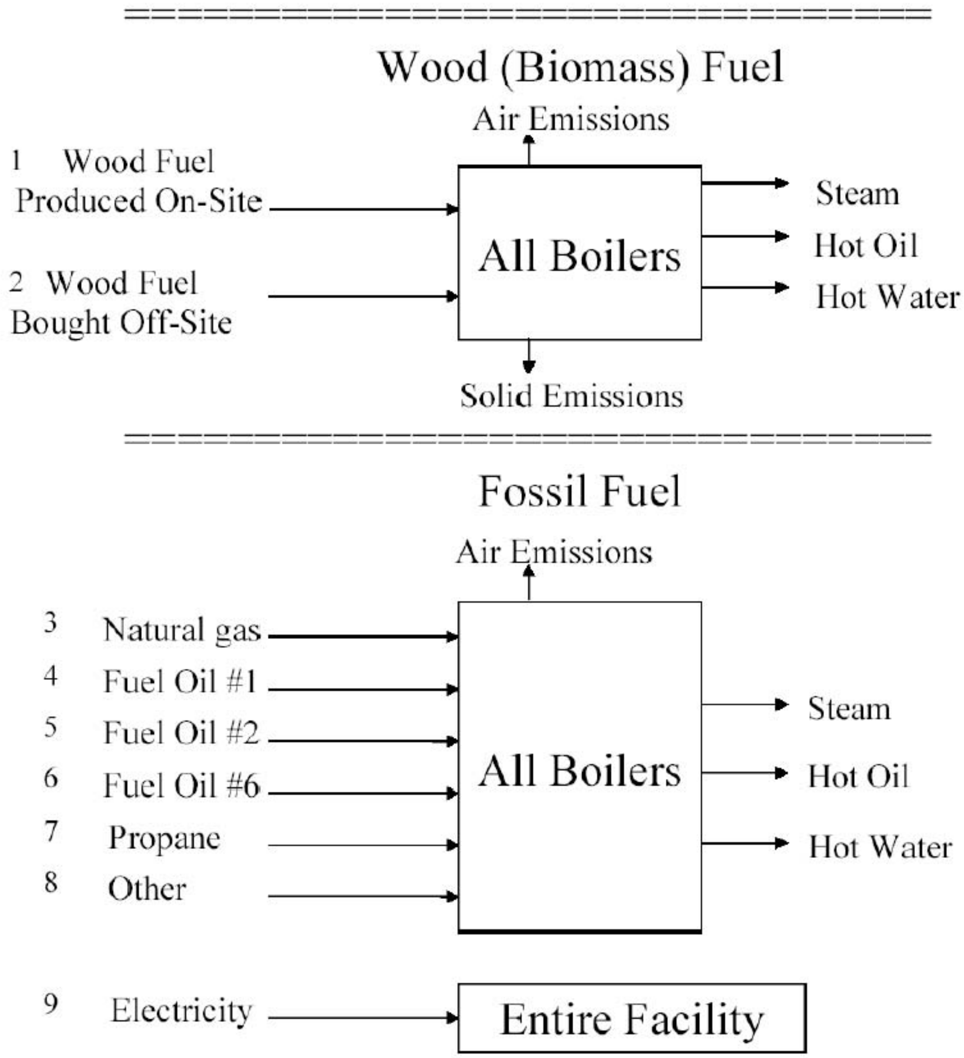
- fuel handling;
- water added to the boiler;
- chemicals added at the boiler or to steam lines;
- distribution of the steam;
- distribution of electricity; and
- the treatment of process air, liquids, and solids.
- The outputs of this unit process are process steam and electricity.

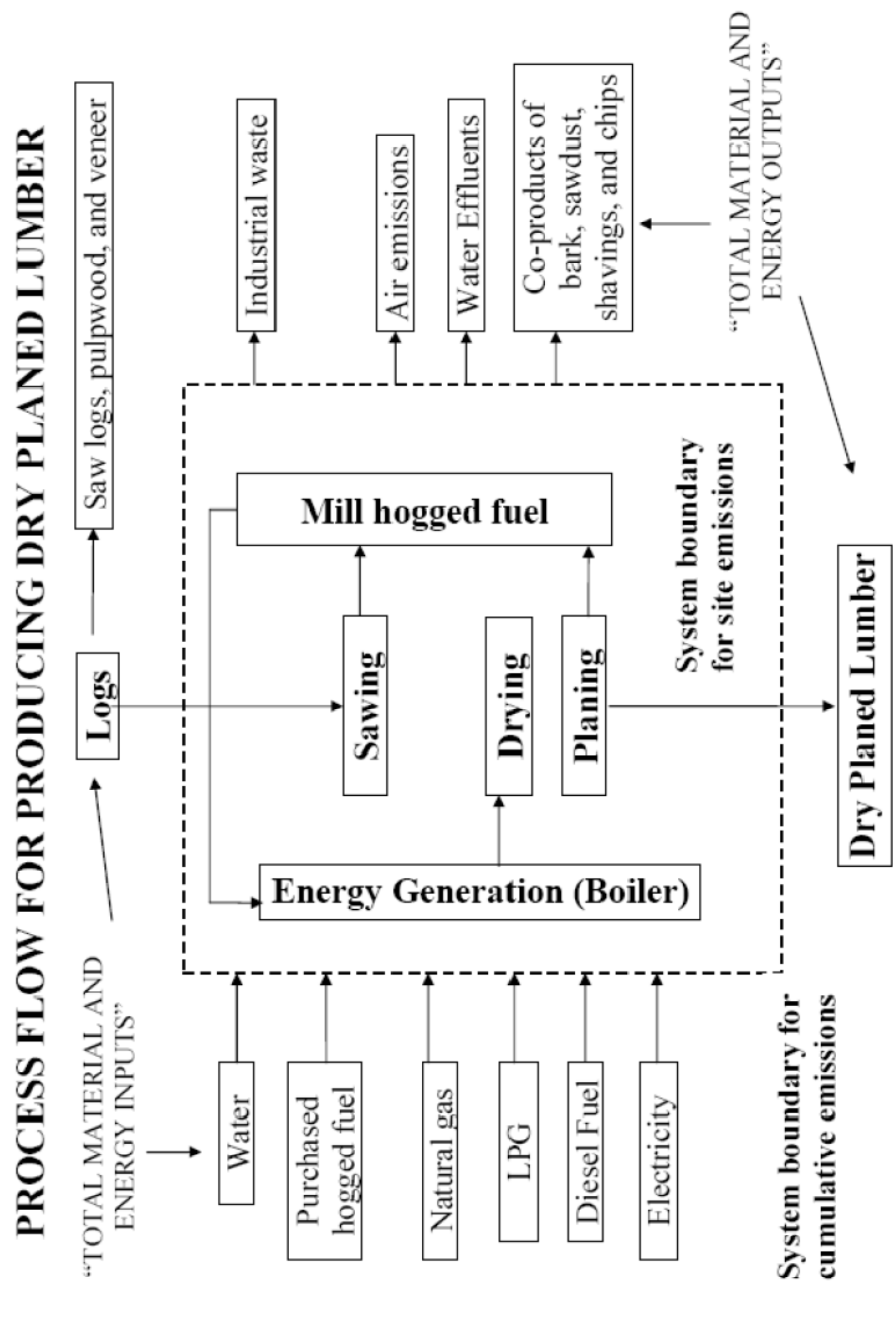
Hardwood Sawmill Block Diagram



Explanations & Diagrams 3 University of Wisconsin Wood Products Division

Energy Generation Block Diagram





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Appendix B: Wood Fuel Types

2.6.4 Wood fuel

2.6.4.1 Types

Distinguishing between various wood fuels is necessary when entering wood fuel values into SimaPro 7. SimaPro lists three types of wood fuels used in this project, distinguished primarily based on energy and material inputs required to process, emissions produced during combustion, and if the fuel was generated at the mill or purchased off-site:

- *Wood fuel* was material generated at the mill for boiler fuel during sawing and planing but has no combustion values assigned to it. Processing values were already assigned to this material.
- *Wood FAL* is a process that includes the cradle-to-gate resource requirements and emissions for providing 1,000 lb of wood (4.5 million Btu in 1996) at 50% moisture content on a wet basis (MC_{WB}) to industrial boilers (i.e. mill gate) (FAL 2003a).
- *Wood into industrial boilers* is a process that includes the cradle-to-gate resource requirements and emissions for the combustion of 1,000 lb of wood (4.5 million Btu in 1996) at 50% MC_{WB} (100% MC_{DB}) in industrial boilers (FAL 2003a).

Wood fuel used at the surveyed mills required different treatments depending on whether the mill processed the boiler fuel on-site or purchased it off-site. For purchased wood fuel, it is necessary to account for the cradle-to-gate resource requirements and emissions to provide purchased wood fuel to the mill gate. The *Wood FAL* category tracked these requirements and emissions. As for on-site generated wood fuel, the softwood lumber LCI already accounted for cradle-to-gate resource requirements and emissions for transporting the wood fuel to the boiler through the incoming logs. *Wood fuel* category accounted for this on-site processing of the material into wood boiler fuel. Both the purchased off-site and generated on-site boiler fuels were fed into the *Wood into industrial boilers* to account for the cradle-to-gate resource requirements to combust this material and emissions released during combustion. Wood fuel generated on-site needed only values assigned to it as cradle-to-gate resource requirements and as emissions related to the combustion of this material—not the wood fuel itself. This is the main difference between generated on-site and purchased off-site wood fuel.

Appendix C-1: LCI Inputs for Logyard Process

Logyard		
Products		
Roundwood at mill, kg, hardwood, SE, USA, U	1290	OD kg
Bark at mill, kg, hardwood, SE, USA, U	53	OD kg
Materials/fuels		
Roundwood at forest road, kg, hardwood, SE, USA, U	1290	OD kg
Bark at forest road, kg, hardwood, SE, USA, U	53	OD kg
Roudwood transport, hardwood, SE, USA, U	144	tkm (wet weight)
Bark transport, hardwood, SE, USA, U	6	tkm (wet weight)
Diesel equipment (gal)	1.69	l
Gasoline equipment (gal)	0.175	l
Natural gas equipment (gal)	0.01	l

Appendix C-2: LCI Inputs for Sawing Process

Sawing		
Products		
Sawn lumber, Hardwood, green, rough, SE, USA, U	1290	OD kg
Wood Fuel, Hardwood, green, SE, USA, U	97	OD kg
Wood Chips, Hardwood, green, SE, USA, U	251	OD kg
Wood Chips (internal use), Hardwood, green, SE, USA, U	33	OD kg
Sawdust, Hardwood, green, SE, USA, U	42	OD kg
Bark, Hardwood, green, SE, USA, U	27	OD kg
Resources		
Water, well, in ground	217	l
Water, process and cooling, surface	25	l
Materials/fuels		
Roundwood at mill, kg, hardwood, SE, USA, U	1290	OD kg
Bark at mill, kg, hardwood, SE, USA, U	53	OD kg
Diesel equipment (gal)	0.85	l
Gasoline equipment (gal)	0.09	l
Natural gas equipment (gal)	0.01	l
Electricity/heat		
Plant Heating, Franklin Boiler, SE Hardwood Lumber Region	155	MJ
Grid Electricity, SE Hardwood Lumber Region	299	MJ
On-Site Electricity, Hardwood Lumber Region	16.7	MJ
Final waste flows		
Material for recycling	0.357	kg
Waste in inert landfill	0.87	kg

Appendix C-3: LCI Inputs for Drying Process

Drying		
Products		
Sawn lumber, Hardwood, rough, kiln dry, SE, USA, U	765	OD kg
Materials/fuels		
Sawn lumber, Hardwood, green, rough, SE, USA, U	765	OD kg
Diesel equipment (gal)	0.85	l
Gasoline equipment (gal)	0.09	l
Natural gas equipment (gal)	0.01	l
Electricity/heat		
Drying, Franklin Boiler, SE Hardwood Lumber Region	4678	MJ
Grid Electricity, SE Hardwood Lumber Region	150	MJ
On-Site Electricity, SE Hardwood Lumber Region	8.4	MJ
Emissions to air		
VOC, volatile organic compounds	0.050	kg

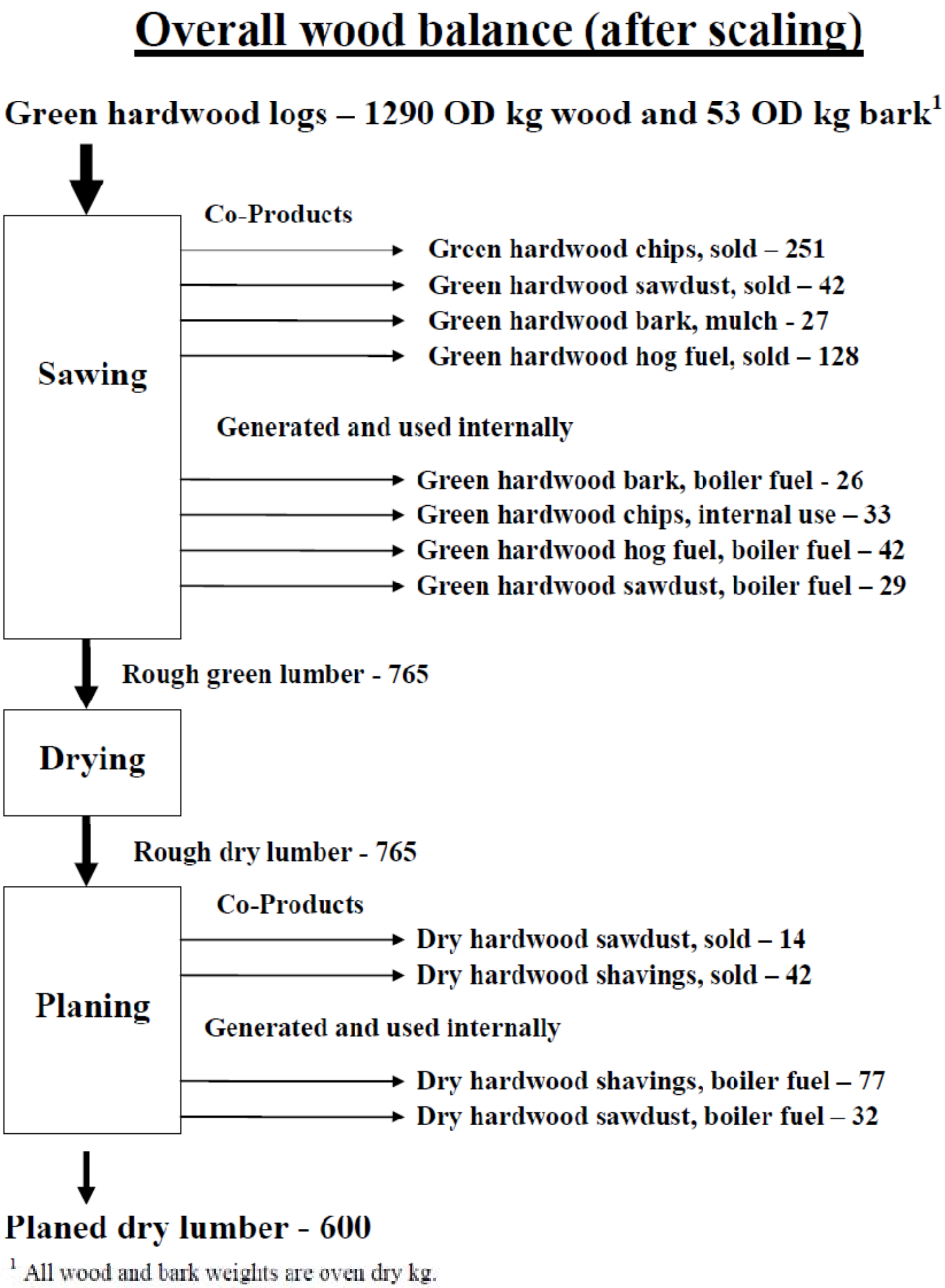
Appendix C-4: LCI Inputs for Planing Process

Planing		
Products		
Sawn lumber, Hardwood, planed, Kiln dry, SE, USA, U	600	OD kg
Wood Fuel, Hardwood, Kiln dry, SE, USA, U	109	OD kg
Shavings, Hardwood, Kiln dry, SE, USA, U	42	OD kg
Sawdust, Hardwood, Kiln dry, SE, USA, U	14	OD kg
Materials/fuels		
Sawn lumber, Hardwood, rough, Kiln dry, SE, USA, U	765	OD kg
Diesel equipment (gal)	0.85	l
Gasoline equipment (gal)	0.09	l
Natural gas equipment (gal)	0.01	l
Electricity/heat		
Grid Electricity, SE Hardwood Lumber Region	150	MJ
On-Site Electricity, NE/NC Hardwood Lumber Region	8.4	MJ

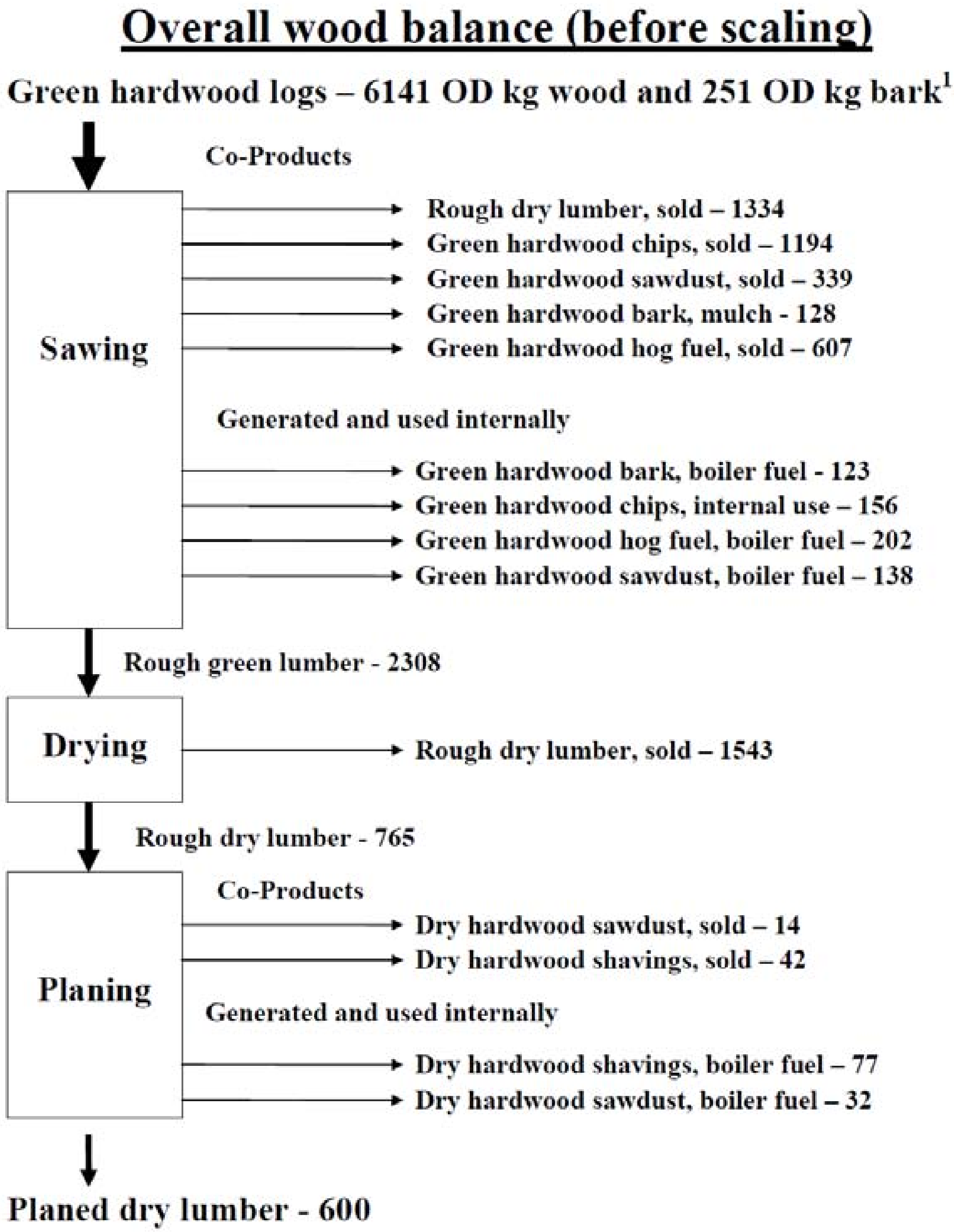
Appendix C-5: LCI Inputs for Energy Generation (Franklin Boiler)

Energy Generation (Franklin Boiler)		
Products		
Drying, Franklin Boiler, SE Hardwood Lumber Region	4678	MJ
Plant Heating, Franklin Boiler, SE Hardwood Lumber Region	155	MJ
On-Site Electricity, SE Hardwood Lumber Region	33.4	MJ
Materials/fuels		
Wood into industrial boilers (purchased), Hardwood, green and Kiln dry SE, USA, U	31.7	OD kg
RFO into industrial boilers	0.49	l
Wood fuel transport, hardwood, SE, USA, U	0.12	tkm (wet weight)
Nat. gas into industrial boilers	3.5	m^3
LPG into industrial boilers	1.46	l
Wood into industrial boilers (generated on-site), Hardwood, green and kiln-dried, SE, USA, U	206	OD kg

Appendix D-1: Wood Material Balance Flowchart for the Production of 1.0 M3 of Planed Dry Lumber



Appendix D-2: Overall Wood Material Balance for the Production of 1.0 M^3 of Planed Dry Lumber (Includes Rough Green and Dry Lumber Co-Products)



[1] All wood and bark weights are oven dry kg.

Appendix E-1: Total Electrical Power Industry by Source for the Southeastern United States for 2005 by State in Megawatthours

AL	Coal	7.81E+07
AR	Coal	2.30E+07
GA	Coal	8.72E+07
LA	Coal	2.31E+07
MS	Coal	1.34E+07
NC	Coal	7.84E+07
SC	Coal	3.97E+07
TN	Coal	5.91E+07
Total	Coal	4.02E+08

AR	Petroleum	2.08E+05
GA	Petroleum	1.03E+06
LA	Petroleum	3.54E+06
MS	Petroleum	1.44E+06
NC	Petroleum	5.19E+05
SC	Petroleum	6.18E+05
TN	Petroleum	2.31E+05
Total	Petroleum	7.59E+06

AL	Natural Gas	1.39E+07
AR	Natural Gas	6.01E+06
GA	Natural Gas	9.77E+06
LA	Natural Gas	4.42E+07
MS	Natural Gas	1.54E+07
NC	Natural Gas	3.16E+06
SC	Natural Gas	5.41E+06
TN	Natural Gas	5.31E+05
Total	Natural Gas	9.83E+07

AL	Other Gases	1.07E+05
LA	Other Gases	1.90E+06
MS	Other Gases	2.02E+04
AL	Other Gases	0.00E+00
SC	Other Gases	5.64E+03
TN	Other Gases	1.46E+04
Total	Other Gases	2.04E+06

AL	Other Biomass	1.64E+04
AR	Other Biomass	2.77E+04
GA	Other Biomass	7.71E+04
LA	Other Biomass	8.04E+04
MS	Other Biomass	5.34E+03
NC	Other Biomass	9.84E+04
SC	Other Biomass	8.77E+04
TN	Other Biomass	6.82E+04
Total	Other Biomass	4.61E+05

AL	Nuclear	3.17E+07
AR	Nuclear	1.37E+07
GA	Nuclear	3.15E+07
LA	Nuclear	1.57E+07
MS	Nuclear	1.01E+07
NC	Nuclear	4.00E+07
SC	Nuclear	5.31E+07
TN	Nuclear	2.78E+07
Total	Nuclear	2.24E+08

AL	Hydroelectric Conventional	1.01E+07
AR	Hydroelectric Conventional	3.08E+06
GA	Hydroelectric Conventional	4.03E+06
LA	Hydroelectric Conventional	8.11E+05
NC	Hydroelectric Conventional	5.40E+06
SC	Hydroelectric Conventional	2.94E+06
TN	Hydroelectric Conventional	9.31E+06
Total	Hydroelectric Conventional	3.57E+07

AR	Pumped Storage	2.07E+04
GA	Pumped Storage	-2.09E+05
NC	Pumped Storage	1.47E+05
SC	Pumped Storage	-1.20E+06
TN	Pumped Storage	-5.98E+05
Total	Pumped Storage	-1.84E+06

TN	Wind	3.34E+03
Total	Wind	3.34E+03

AL	Other	2.51E+04
AR	Other	1.53E+04
GA	Other	5.25E+04
LA	Other	5.50E+05
MS	Other	6.95E+03
NC	Other	3.03E+05
SC	Other	9.37E+04
TN	Other	8.60E+03
Total	Other	1.05E+06

AL	Wood and Wood Derived Fuels	3.63E+06
AR	Wood and Wood Derived Fuels	1.71E+06
GA	Wood and Wood Derived Fuels	3.19E+06
LA	Wood and Wood Derived Fuels	2.81E+06
MS	Wood and Wood Derived Fuels	1.52E+06
NC	Wood and Wood Derived Fuels	1.71E+06
SC	Wood and Wood Derived Fuels	1.73E+06
TN	Wood and Wood Derived Fuels	6.95E+05
Total	Wood and Wood Derived Fuels	1.70E+07

Lippke, Bruce, Jim Wilson, Leonard Johnson, Maureen Puettmann. 2009. Phase II Research Report. Life Cycle Environmental Performance of Renewable Materials in the Context of Building Construction. Module L : **Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Southeastern United States** by Richard D. Bergman and Scott A. Bowe. [Seattle, WA] : CORRIM, 2010. 50 p