LIFE-CYCLE INVENTORY OF MANUFACTURING HARDWOOD LUMBER IN SOUTHEASTERN US[1]

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Abstract. Environmental impacts associated with the building industry have become of increasing importance. Materials and energy consumed during manufacture of building materials such as lumber affect a building's environmental performance. This study determined environmental impacts of manufacturing hardwood lumber in the southeastern US using the life-cycle inventory method. Primary data were collected and then weight-averaged on a per-unit basis of 1.0 m^3 of planed dry lumber (600 oven-dry kg/m^3) to find material flows and energy use. Cumulative allocated energy consumption for manufacturing 1.0 m^3 planed dry lumber from 2.44 m^3 of incoming logs was 5.86 GJ/m^3 with 66% from wood fuel. Emission data produced through modeling estimated total biomass and fossil carbon dioxide production of 424 and 131 kg/m^3, respectively, considering all impacts. A cubic meter of planed dry hardwood lumber stores 1.17 Mg CO_2 equivalents as a final product. The amount of carbon stored in hardwood lumber exceeds fossil carbon emissions by a factor of nine. Therefore, as long as hardwood lumber and its carbon stay in products held in end uses, carbon stored will exceed fossil carbon emitted in manufacturing.

Keywords: Life-cycle inventory, hardwood lumber, southeastern US, LCI, CORRIM, gate-to-gate, green building, manufacturing.

INTRODUCTION

Hardwood lumber from species in the southeastern (SE) US is used primarily for pallets, crossties, flooring, millwork, cabinets, and furniture. Total annual US hardwood lumber production in 2005 and 2006 was 26.4 and 26.0 Mm^3, respectively. Most hardwood lumber is consumed domestically, but an estimated 3.12 Mm^3 was exported in 2006. In addition, the US imported 882 km^3 in 2006 (USDC 2007). Domestic hardwood lumber production occurs mostly in the eastern US and is divided roughly equally between SE and northeastern and north central (NE/NC) US. A smaller percentage, approximately 3.3%, of hardwood lumber production occurs in the Pacific northwestern (PNW) US. Annual hardwood lumber production has declined considerably in the last several years. Production in 2010 was 12.6 Mm^3 (USDC 2011a). Rough green hardwood lumber is used in pallets and crossties, whereas most planed dry lumber is converted into building products for new construction and repair and remodeling of existing buildings.

Energy consumption and environmental impacts of manufacturing residential building products are playing an increasingly important role in the

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building industry because of increased public awareness of environmental issues. In the US, total consumption of hardwood lumber decreased slightly from 30.4 Mm^3 in 1999 to 26.4 Mm^3 in 2006. Also, sharp declines have occurred during the last several years to levels not noted since 1963. Consumption in 2010 is estimated to be 16.3 Mm^3 with a slight increase expected in 2011 (Luppold and Bumgardner 2008; Hardwood Market Report 2009; Johnson 2011; Luppold 2011). Furthermore, a large drop occurred in the single-family residential construction seasonally adjusted annual rate from a high of 1.64 million in 2005 to 0.453 million in October 2011 (USDC 2011b). As shown, residential housing has a significant effect on lumber consumption. A considerable drop in hardwood lumber consumption has occurred since the recession. One factor offsetting the decrease in residential housing is the average size of single-family residences being constructed, which increased from 193 m^2 in 1991 to 222 m^2 in 2010, a 15% increase (USDC 2011b). However, increasing environmental concerns regarding the residential building industry help define "green building" materials and practices.

Green building refers to the practice of improving energy efficiency of materials, construction, and operation and decreasing overall environmental burdens of buildings. The green building market for new nonresidential construction is likely to triple from $42 billion in 2008 to $96-140 billion by 2013 (MHC 2010). Also, annual demand for green building materials is likely to increase from $38.7 billion as of 2010 to about $70 billion in 2015 (Freedonia 2011). Forming a sound policy for building practices, especially for green building in the US, would significantly decrease the environmental impact on the world's resources. However, to help develop such a policy, life-cycle information is necessary to evaluate building materials and practices for their environmental impacts.

Precise baseline life-cycle inventory (LCI) data are needed as part of this broader scientific approach for determining building styles, type of construction materials, and potential product improvements with a focus on decreasing environmental burdens. This LCI study examined the environmental impact of hardwood lumber production in the SE US. Also, LCI data from this study and other wood product LCI studies are in the US LCI database managed by the National Renewable Energy Laboratory (NREL 2011). Inclusion in the US LCI database allows other life-cycle assessment (LCA) practitioners to complete either a cradle-to-gate LCI or LCA of hardwood-lumber-related wood products (Puettmann et al 2010a).

LCI provides an accounting of energy and waste associated with creation of a product through use and disposal. In this study, gate-to-gate LCI tracked hardwood lumber production from transport of logs from a forest landing to a log yard and through all steps in lumber manufacturing including drying and planing. 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. Cradle-to-grave LCA is beyond the scope of this study. In this LCI study, tracking the material flow of hardwood lumber is necessary for an accurate survey of different unit processes.

Material flow is tracked from raw material—hardwood logs—to planed (surfaced) dry hardwood lumber (the final product). Rough green (freshly cut) lumber sawn from hardwood logs is typically dried in conventional dry kilns burning wood residue (woody biomass) and fossil fuels as heat sources. It is estimated that nearly 90% of all hardwood lumber dried in the US uses energy produced with wood biomass from milling processes (Denig et al 2000; Bergman and Bowe 2008). Not all rough green hardwood lumber is kiln-dried. The sawing process consumes the greatest percentage of electrical energy. Before drying, boards are stickered (separated by thin wood strips) and stacked to aid drying and prevent drying defects. The drying process consumes 70-80% 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.

The goal of this study was to document LCI of planed dry lumber production from hardwood logs and determine material flow, energy use, solid waste, and emissions for the hardwood lumber manufacturing process on a per-unit basis for the SE US (Fig 1). We calculated primary mill data from questionnaires mailed to lumber mills. Also, we used secondary data from peer-reviewed literature per ISO (2006a, 2006b) guidelines. We calculated material and energy balances by a spreadsheet algorithm using data from primary and secondary data sources. From weight-averaging these material and energy values, environmental impacts were estimated by modeling emissions through SimaPro 7 software (PRé Consultants, Amersfoort, The Netherlands) (PRé Consultants 2011). SimaPro has been used in many previous Consortium for Research on Renewable Industrial Material (CORRIM) -initiated LCI projects such as those focused on production of hardwood lumber (Bergman and Bowe 2008) and softwood lumber (Milota et al 2005; Bergman and Bowe 2010a; Puettmann et al 2010b). This LCI study conformed to relevant ISO standards (ISO 2006a, 2006b).

METHODS

In this study, forestry operations, including harvesting, were excluded but are documented in other CORRIM Phase II projects (Johnson et al 2008; Puettmann et al 2010b). Transportation data for raw materials to sawmills were collected as part of this study. The LCI study covered the year 2006 and included log yard activities, sawing of hardwood lumber, drying, and planing. Mill surveys provided primary data for LCI analysis, whereas secondary data for production and transportation of fuels and electricity were obtained from published databases (FAL 2004; NREL 2011; PRé Consultants 2011).

A large number of commercial hardwood species are sawn in the SE. Table 1 shows the percentage of mill throughput by species for the 12 mills surveyed in this study and their location by state. Three mills processed hardwood and softwood lumber, but production data from softwood lumber were not used in this evaluation.

Figure 1. Shaded area was selected for life-cycle inventory of hardwood lumber production in southeastern US.

Table 1. Species data for participating mills.

	Species mix[a] by percentage													
Mill	RO	WO	HM	SM	Hackberry	Pecan	Hickory	Cypress	YP	Cottonwood	Ash	Gum	Misc.	SW	State
A	58	14	0	0	0	0	0	0	0	0	0	0	7.0	21	MS
B	21	13	0	0	0	0	0	0	56	0	0	0	10	0	NC
C	78	19	0	0	0	0	0	0	1.0	0	2.0	0	0	0	AL
D	66	5.7	0	0	0	0	0	2.4	15	5.8	4.9	0	0	0	MS
E	25	12	0	0	0	0	0	5.6	16	15	0	17	10	0	TN
F	11	10	0	3.0	0	0	0	0	23	0	0	0	3.4	50	NC
G	76	12	0	0	0	0	0	0	8	0	3.0	0	1.0	0	MS
H	7.0	0	21	0	0	0	0	16	56	0	0	0	0	0	NC
I	34	7.0	0	0	8.0	6.0	0	6.0	0	0	12	7.0	8.0	12	LA
J	68	15	0	0	0	0	0	0	7.0	0	0	0	10	0	MS
K	25	10	9	0	0	0	0	29	22	0	5.0	0	0	0	NC
L	40	15	5	0	0	0	8.0	0	15	0	5.0	0	12	0	TN
Total	45.4	10.6	1.6	0.4	1.5	1.1	0.4	3.5	14.9	0.8	3.8	1.8	4.9	9.3	—

[a] RO, red oak; WO, white oak; HM, hard maple; SM, soft maple; YP, yellow poplar; SW, softwood.

The LCI of hardwood lumber from the SE US was an extension of the LCI on hardwood lumber for the NE/NC US as part of CORRIM Phase II product LCI (Bergman and Bowe 2008). The project and the results may be used by LCI practitioners for LCA studies that document the use of wood products in building construction during the entire life cycle (cradle-to-grave). Life-cycle information given in this study is also available from the US LCI database (NREL 2011). Critical external reviews of this LCI process were conducted to ensure compliance with CORRIM guidelines and the ISO 14044 standard (ISO 2006b; CORRIM 2010).

Hardwood Lumber Manufacturing and Five Main Unit Processes

Five main unit processes were identified in producing hardwood lumber—resource transport, log yard, sawing, drying, and planing (Fig 2)—with energy generation as an auxiliary process. We chose mass allocation because the highest volume product had the greatest economic value. This was true for all unit processes.

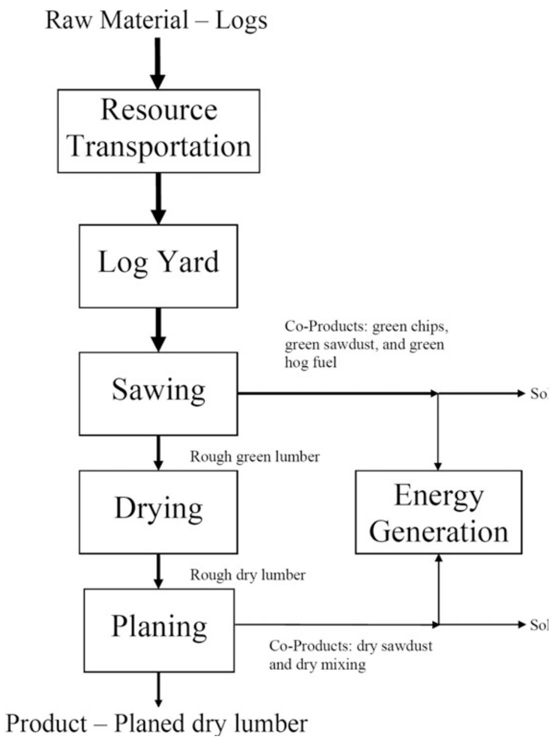

Figure 2. Material flow for the five unit processes of hardwood lumber manufacturing.

Resource transport. Production started with transport of hardwood logs (ie roundwood) from the forest landing to the sawmill and storage in the log yard. Inputs included diesel fuel to run logging trucks.

Log yard. Log yard operations began with hardwood logs in the yard with impacts monitored from the yard to the sawmill. Logs were stored dry or wet, depending on species and season. Forklifts/loaders transported logs from the yard to the sawmill infeed and log bucking saw and/or debarker.

Sawing. Sawing started with logs at the debarker. In the sawing process, incoming hardwood logs (raw material) were sawn into mostly 25- and 50-mm-thick rough green (freshly cut) lumber of random widths and mostly 2.44- to 3.66-m lengths. Dimension sizes were nominal. Rough green lumber was then tallied (to measure production volume) and stickered for drying. The outputs of this unit process included sawn rough green lumber and wood residue from the sawing process: bark, sawdust, slabs, edgings, and chips (hog fuel was a mixture of the wood residues produced). For the survey data, slabs and edgings fell under either hog fuel or chips. Most green wood residues (77%) were sold as a coproduct; others (17%), especially sawdust, were burned as boiler fuel to generate heat for drying lumber and a little electricity. The remaining wood residue (6%) produced saleable goods such as mulch (bark) and pulp chips.

Drying. Drying began with rough green lumber. Lumber was dried to 6-8% MC using mostly energy-intensive drying methods such as kiln-drying, although some prior air-drying and predrying occurred. The output of this unit process was rough dry lumber, and the majority of this material was transported by forklift to the planer mill. Drying generated most of the volatile organic compounds (VOCs) generated on-site and used the most energy produced from both wood and fossil fuel combustion. For the 12 surveyed mills, initial moisture content was 85% for rough green lumber and on average 8% for rough dry lumber. Drying methods used depended on species, lumber thickness, lumber grade, final use, and available wood residue markets. Typical sawmills used a kiln schedule when drying lumber to maintain high quality by preventing drying defects. Most rough green lumber (about 63%) was kiln-dried at the mill.

Planing. After drying, rough dry lumber was planed to the dimension required for the final product. Some planed lumber was only blanked or skip (hit or miss) planed. Only a small portion of rough green lumber that was kiln-dried (about 21%) was planed at the mill. Planing started with stickered, rough dry (kiln-dried) lumber and ended with planed (surfaced) and packaged lumber sorted by type, size, and grade as well as planer shavings, sawdust, and/or lumber trim ends. This process was the final stage of manufacturing. About 66% of dry wood residue was burned on-site in boilers for energy, whereas the rest was sold as coproducts.

Auxiliary energy generation. This auxiliary process provided heat and in some cases electricity for use in other parts of the mill. Mills burned fuels such as wood or natural gas; green and kiln-dried wood residue from the sawing and planing processes generated most of the thermal energy used at the plant. Thermal energy was typically in the form of steam used for dry kilns, steam generators, and facility heating. Another major source of energy was off-site (grid) electricity. Grid electricity released emissions off-site. Outputs of this auxiliary process were steam and hot water from boilers, combustion gases for drying, electricity from cogeneration units, solid waste (wood ash), and air emissions (eg CO_2, CO) from combustion.

Coproducts from the manufacturing process included both sold material and wood residue burned on-site for energy generation. In this study, byproducts were also referred to as coproducts because all wood residual whether used on-site and sold off-site was used. In this LCI study, when referring to logs, lumber, and other coproducts, the term green was used in the context of freshly cut material.

Functional Unit

Material flows, energy use, and emission data were standardized to a per-unit volume basis of 1.0 m^3 planed dry hardwood lumber, the final product of the hardwood lumber manufacturing process. According to standard grading rules, nominal and actual dimensions of hardwood lumber are equivalent only when lumber is rough dry. A typical conversion from cubic meters to thousand board feet (MBF) based on nominal dimensions is 0.424 MBF/m^3 (2.36 m^3/MBF). For dry planed lumber of thickness assumed in this study, the conversion is 0.595 MBF/m^3 (1.68 m^3/MBF). Rough green lumber and rough dry lumber were assumed to be 2.44 and 2.13 m^3/nominal MBF, respectively (Fonseca 2005; Bergman 2010). Allocating all material and energy on a per-unit basis of 1.0 m^3 planed dry lumber standardized the results to meet ISO standards, allowing unit processes to be used to construct a cradle-to-gate LCI and LCA (ISO 2006a, 2006b; CORRIM 2010).

System Boundaries

Boundary selection was important because material and energy that cross the boundary must be accounted for in the gate-to-gate LCI. Two system boundaries were considered in tracking environmental impact of hardwood lumber production. One—the cumulative system boundary—is shown by the solid line in Fig 3 and is inclusive of both on-site and off-site emissions for all material and energy consumed. Included within this cumulative system boundary are fuel resources used for energy and electricity production. The site system boundary (dotted line in Fig 3) encompassed emissions developed only at the hardwood sawmill (ie on-site) from the four unit processes involved: log yard operations, sawing, drying, and planing. Examples of off-site emissions were grid electricity production, transportation of logs to the mill, and fuels produced off-site but used on-site.

Project Assumptions and Limitations

Bergman and Bowe (2010b) provided detailed assumptions and limitations for determining results of this LCI study (ISO 2006a).

RESULTS AND DISCUSSION

Product Yields

Mass and energy values, including emissions for hardwood lumber production, were obtained for 2006 by surveying 12 mills in the SE US that

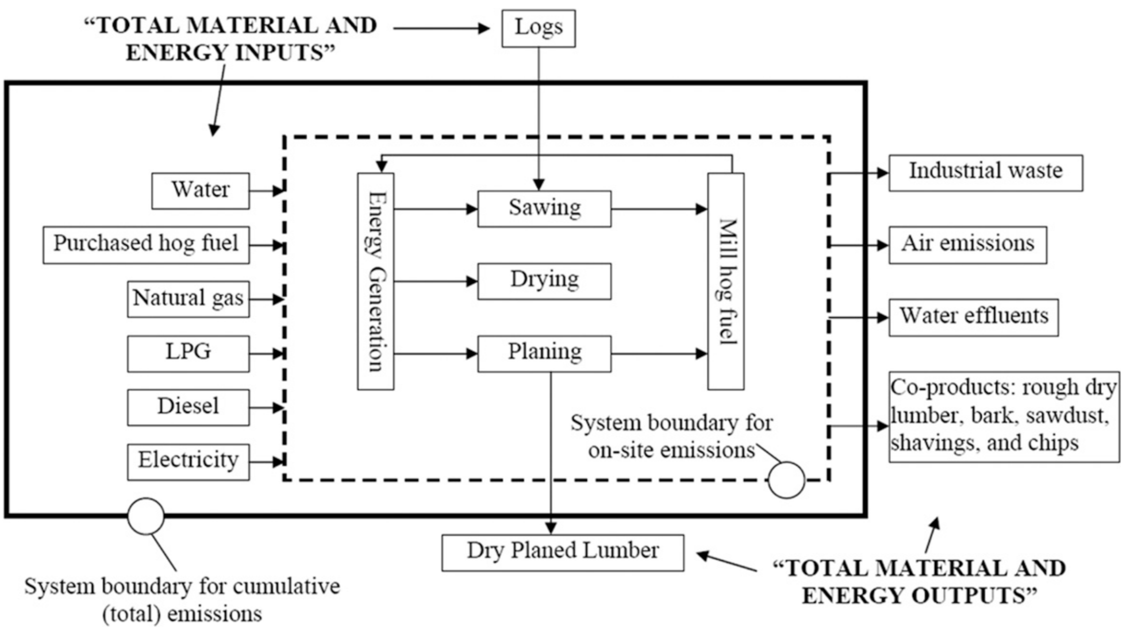

Figure 3. System boundaries for hardwood lumber production.

provided detailed primary data on mass flow, energy consumption, and types of fuel. SimaPro 7 was used to estimate nonwood raw material use and emission data on a 1-m^3 unit basis by modeling weight-averaged survey data.

Total 2006 annual hardwood lumber production for this area was 8.76 Mm^3 (USDC 2007). The 12 mills produced 576 km^3 rough green lumber, which represented about 6% of the total annual 2006 US production from this region. This 6% value exceeded the minimum CORRIM protocol guideline of 5% for data representation (CORRIM 2010). Also, 365 and 121 $km^3$of rough dry lumber and planed dry lumber, respectively, were produced from this 576 km^3 of rough green lumber. Not all rough green lumber was kiln-dried nor was all rough dry lumber planed.

Weight-averaged annual production for the 12 hardwood sawmills was 76.4 km^3 with a range of 17.4-131 km^3. For the NE/NC, a large production hardwood lumber mill is considered 30.8 km^3 or more (Bergman and Bowe 2008). The weight-averaged log diameter was 396 mm, and production kiln capacity was 1.00 km^3. Pulp chips comprised the greatest proportion of wood residue produced at 284 oven-dry (OD) kg/m^3 planed dry lumber (Table 2).

In performing a mass balance, all unit processes within the site system boundary were considered. Using a weight-averaged approach, 1.29 OD Mg of incoming hardwood logs with a green density of 977 kg/m^3 produced 1.0 m^3 (600 OD kg) of planed dry lumber. Sawing yielded 765 kg of rough green lumber, and no loss of wood substance occurred in the drying process. Planing decreased the 765 OD kg of rough dry lumber to 600 OD kg of planed dry lumber for a 21% decrease in mass. Some of the wood was converted on-site to thermal energy in a boiler; boilers burned 206 OD kg of both green and dry wood fuel produced on-site (Table 2) for thermal process energy. Overall, an average log was decreased to 46.5% of its original mass in conversion to the final product of planed dry lumber.

Most mills in the US use volumetric values such as board feet log scale to purchase logs and a lumber tally as a basis for selling lumber. Mill efficiency, therefore, cannot be determined directly. The lumber recovery factor (LRF) is one way to track efficiency. LRF quantifies productivity as the nominal board foot lumber tally recovered per volume of log input. For mills assessed in this study, 2.44 m^3 of hardwood logs was sawn into lumber (1.45 m^3), dried (1.27 m^3), and planed into the final product of 1.0 m^3 of planed dry lumber for a total volume conversion of 41.0% of incoming logs. The difference in the conversion value (41%) and mass conversion efficiency (46.5%) was

Table 2. Weight-averaged wood mass balance (OD kg per m^3 planed dry lumber).

	Sawing process				Drying process		Planer process		All processes combined		
Material	Input	Output	Internal process input	Boiler process input	Input	Output	Input	Output	Input	Output	Difference
Green logs[a]	1290	—	—	—	—	—	—	—	1290	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
Sum	1340	1340	33	206	765	765	765	765	3110	2870	–239

[a] Log wood volume only.
[b] Log bark volume.
OD, oven-dry.

caused by lumber shrinkage during the drying process.

Energy Consumption

Hardwood lumber production requires both electrical and thermal energy for processing logs into planed dry lumber. For mills examined in this study, all thermal energy was produced on-site, whereas most electricity was 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 used in the drying process. Of the total 5.167 GJ of unallocated process energy consumed per cubic meter of planed dry lumber, 4.678 GJ was for drying, 334 MJ was for on-site electrical generation (cogeneration), and 155 MJ was for plant heat. Cogeneration, on average, yielded 33.4 MJ of electrical energy from 334 MJ of thermal energy. The total unallocated electrical consumption that does not include primary energy was 631 MJ/m^3 of planed dry lumber. Primary energy is energy embodied in natural resources such as fossil fuels and biomass before being converted, for example into electricity or heat. The value of 631 MJ/m^3 included both off-site and on-site electrical sources (Table 3). For sawing, drying, and planing, the distribution of grid electrical energy consumption was 50, 25, and 25% of the total, respectively. Based on these percentages, the three unit processes used 299, 149.5, and 149.5 MJ of grid electricity per cubic meter planed dry lumber. Wood-fuel cogeneration provided 5.3% of total electricity consumed. Process energy use varied considerably, depending on if the mill ran a cogeneration unit. Larger mills tended to use less energy per unit of planed dry lumber for drying than did smaller mills.

Process energy required for drying and other associated drying processes (including cogeneration) and facility heating was 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, were combusted to generate heat for the mill per 1.0 m^3 planed dry lumber. Thermal energy produced on-site was the greatest proportion of energy used on-site. Overall, wood fuel contributed 96% to total energy produced on-site with natural gas at 2.6%.

Table 3. Material and energy consumed on-site to produce 1.0 m^3 of planed dry lumber (SimaPro input values).[a]

Fuel type	Amount (units/m^3)
Fossil fuel[b]	
Natural gas	3.5 m^3
Fuel oil #6	0.49 L
Propane	1.46 L
Electricity	
Off-site generation	598 MJ
On-site generation	33 MJ
On-site transportation fuel[c]	
Off-road diesel	4.23 L
Gasoline	0.44 L
Propane	0.04 L
Renewable fuel[d]	
On-site wood fuel	206 kg
Purchased wood fuel	31.7 kg
Water use	
Surface water	25.4 L
Groundwater	217 L

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (unallocated).
[b] Energy values were determined using higher heating values (HHV) in MJ/kg: 43.3 for fuel oil #1 and #2.
[c] Energy values were determined using 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).

Total energy consumption per cubic meter of planed (surfaced) dry hardwood lumber was comparable with published data (Comstock 1975; Breiner et al 1987; Armstrong and Brock 1989; Bergman and Bowe 2008), allowing for the fact that processes such as facility heating and cogeneration were included in this analysis because their energy use was significant. Electrical consumption for producing planed dry hardwood lumber in the SE was similar to the NE/NC US with an overall value of 608 MJ/m^3 (Bergman and Bowe 2008). Neither value considers primary energy resources.

As part of ISO 14040 guidelines, ways to decrease environmental burdens are included in this study. Decreasing energy consumption is a common way to decrease environmental burdens and is consistent with what was found in this study. There are several approaches to lowering energy consumption, and mills that incorporate these methods would ultimately have significantly lower energy use and therefore increased productivity. Using improved sawing practices, such as the best opening face program (Harpole and Hallock 1977), improved lumber sizing, and thinner kerf saws, has increased lumber yields and decreased electricity consumption. Most large mills are using these technologies. Curve sawing technology is another approach that is already standard practice in the softwood lumber industry (Bond and Araman 2008).

Another approach is to decrease thermal energy use. Several different drying methods including altered kiln schedules may be used depending on species, fuel costs, and wood residue use. Air-drying lumber is one such method, but this is not the preferred method because of drying degrades and the large amount of drying stock required. One surveyed mill had an extensive air-drying yard and as a result had considerably decreased energy consumption. Drying degrade is a decrease in lumber quality caused by drying; greater control of the drying process typically decreases drying degrade, for example, drying lumber in a T shed or covering lumber with a protective fabric. Maintaining a large lumber inventory for air-drying decreases profits because recovering investments is delayed. Among drying methods, air-drying has the least control, resulting in the highest level of degrade, although it requires the lowest energy use of all drying methods (FPL 1999; Denig et al 2000; Nebel et al 2006).

Table 4 shows allocated cumulative energy of making 1.0 m^3 of planed dry lumber (solid line system boundary). Cumulative energy allocated to planed dry lumber was 5.86 GJ/m^3. Of the different types of fuel, wood fuel/wood waste consumed by far the most energy, because of the intensive energy needed for kiln-drying lumber.

On-site transportation of wood was a minor fuel consumer compared with boiler fuel consumption.

Table 4. Cumulative energy (higher heating values [HHV]) consumed during production of planed (surfaced) dry hardwood lumber—cumulative, allocated gate-to-gate life-cycle inventory values (SimaPro output values).[a]

	Southeast lumber (SE)	
	(kg/m^3)	(MJ/m^3)
Fuel[b,c]		
Wood fuel/wood waste	184	3860
Coal[d]	31.4	823
Natural gas[d]	6.90	375
Crude oil[d]	7.64	348
Hydro	0	19
Uranium[d]	0.00112	427
Energy, unspecified	0	10
Total	—	5860

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).
[b] Values are allocated and cumulative and based on HHV.
[c] Energy values were found using their 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.
[d] Materials as they exist in nature and have neither emissions nor energy consumption associated with them.

Off-road diesel accounted for the greatest consumption. On-site transportation included forklifts, front-end loaders, trucks, and other equipment used within the system boundary of the facility. Off-road diesel consumption was 4.23 L/m^3 of planed dry lumber and was consumed at nearly nine times the rate of propane and gasoline combined on average. Transportation fuel consumption for unit processes was 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 were 1.69, 0.846, 0.846, and 0.846 L/m^3. For propane, values were 0.175, 0.088, 0.088, and 0.088 L/m^3, respectively.

Off-site generation of electrical power significantly influenced overall environmental impact because of all the different fuels used to generate power. Grid electricity is produced off-site (beyond the mill's boundary) for use on-site in the manufacturing process. Average composition of (off-site) electricity was determined for the SE region by totaling quantities of different fuel sources used in electrical generation for each of the eight states in 2006 and converting to percentages. The most significant electric power contributor in the SE region was coal (51.1%).

Other contributors were nuclear (28.4%), natural gas (12.8%), petroleum (1.2%), hydro (2.5%), and other renewables (1.9%).

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 used both types of wetting logs and one did not wet its logs. Water consumption was based on responses from six mills with one mill using nearly 70% of total reported consumption for sprinkling logs. Dust control was a problem for several mills with gravel-surfaced air yards, especially during the dry season. Surface and groundwater consumption averaged 25.4 and 217 L/m^3 of planed dry lumber, respectively. Factoring out the one large water-consuming mill decreased average groundwater consumption to 61.3 L/m^3, about a 71.8% decrease, whereas average surface water consumption stayed the same.

Transportation Data

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 logs (including bark) of 60.4 km with 100% empty backhaul was calculated from primary mill data. Mill average log moisture content was 85%.

Purchased wood fuel. Only one mill surveyed purchased wood fuel for heating dry kilns and for operating a cogenerating unit. The mill's cogeneration unit provided both thermal and electrical energy for use on-site. An average one-way haul distance for purchased wood fuel of 3.64 km with 100% empty backhaul was calculated from primary mill data. Mill average purchased wood fuel moisture content was 8%.

Environmental Impact

SimaPro 7 was used to model output factors such as raw material consumption during the manufacturing process on an allocated basis. Excluding logs processed into lumber, raw materials consumed included 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 5). Limestone and most of the coal were used to produce off-site electricity, and oil and natural gas were 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 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 PNW is produced from hydro and natural gas.

Life-Cycle Inventory

Two different LCI scenarios for manufacturing hardwood lumber were evaluated: allocated

Table 5. Raw materials consumed during production of planed (surfaced) dry lumber—cumulative, allocated gate-to-gate life-cycle inventory values (SimaPro output values).[a]

Raw material[b]	Amount[c] (units/m^3)
Logs at mill gate[d]	1.27 m^3
Water, well, in ground[e]	0.126 m^3
Water, process and cooling, surface[e]	0.014 m^3
Purchased wood waste	24.6 kg
Coal, in ground[e]	31.4 kg
Gas, natural, in ground[e]	6.90 kg
Oil, crude, in ground[e]	7.64 kg
Limestone, in ground[e]	4.92 kg
Energy, from hydro power[f]	18.5 MJ
Energy, unspecified[f]	10.3 MJ
Uranium, in ground[e]	0.00112 kg

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).

[b] Values are allocated and cumulative.

[c] 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.

[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.

cumulative and allocated on-site. The method for evaluating the two scenarios followed ISO 14040 standards, and SimaPro was used as an assessment tool. The allocated cumulative scenario 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 forest landing. Emissions included cradle-to-gate resource requirements (production and delivery) of grid electricity, fossil fuels, and purchased wood fuel burned in the boiler and fossil fuels used in yard equipment such as forklifts. This scenario also included emissions data from on-site combustions of purchased wood fuel, fossil fuels, and wood fuel generated on-site burned in boilers for process energy. Transportation of logs (including bark) to the mill gate was included in the first scenario. The allocated on-site scenario only considered emissions from combustion of all fuels used on-site at the mill and therefore did not include logging or transport of logs to the mill, manufacture of liquid fuels, or off-site grid electricity consumed at the mill.

Table 6 shows the lower environmental impact of on-site compared with cumulative emissions for the 12 mills surveyed. Carbon dioxide (CO_2) emissions were separated by two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Biogenic CO_2 is considered carbon-neutral when the CO_2 emitted is reabsorbed during forest growth and released during decomposition or burning and done on a sustainable basis. Cumulative (total) emission values of 424 and 131 kg were reported from SimaPro for CO_2 (biogenic) and CO_2 (fossil), respectively (Table 6). Percentage of biogenic CO_2 to total CO_2 increased from 76.4 to 91.5% from total to on-site schemes. VOCs produced from drying lumber were 43 g/m^3 regardless of scenario. This is close to the value of 50 g VOCs/m^3 of rough green lumber as calculated from the literature (Rice and Erich 2006; Rice 2008).

Materials and energy resources consumed to manufacture 1.0 m^3 of planed dry hardwood lumber are shown in Table 3. Table 7 shows on-site energy input values unallocated and allocated to planed dry lumber. Unallocated values were calculated from material and energy resources found in Table 3 and were the sum of all fuel and electricity inputs to the process. Allocated on-site energy use is roughly 75% of total unallocated on-site use.

Table 6. Life-cycle inventory results for total emissions on a per unit basis of planed dry lumber.

Substance	Allocated total (kg/m^3)	Allocated on-site (kg/m^3)
Water emissions		
Biological oxygen demand (BOD)	4.98E-04	3.78E-07
Cl^-	1.96E-02	1.78E-05
Suspended solids	5.33E-02	2.09E-04
Oils	7.71E-03	—
Dissolved solids	4.27E-01	6.35E-05
Chemical oxygen demand (COD)	5.25E-03	3.24E-05
Other solid material[a]		
Waste in inert landfill	0.505	0.505
Waste to recycling	0.207	0.207
Solid waste[b]	33.2	18.2
Air emissions		
Acetaldehyde	6.05E-04	6.07E-04
Acrolein	1.12E-06	—
Benzene	7.27E-04	7.28E-04
CO	3.57	3.43
CO_2 (biomass)	424	424
CO_2 (fossil)	131	39.4
CH_4	1.97E-01	1.94E-04
Formaldehyde	1.12E-02	1.12E-02
Mercury	2.41E-06	2.46E-07
NO_x	1.37	0.95
Nonmethane, volatile organic compounds (NMVOC)	2.05E-01	6.82E-02
Particulate (PM10)	1.12E-01	8.25E-02
Particulate (unspecified)	7.99E-02	—
Phenol	8.07E-03	8.09E-03
SO_x	0.848	0.103
VOC	0.0430	0.0430

[a] Includes solid materials not incorporated into product or coproducts and outside of the system boundary.

[b] Solid waste is mostly boiler ash from burning wood. Boiler ash is either spread as a soil amendment or landfilled depending on the facility.

Table 7. Fuel and electrical energy used to produce a cubic meter of planed dry lumber.

	Energy use at mill	
	Unallocated (MJ/m^3)	Allocated (MJ/m^3)
Fossil fuel[a]		
Natural gas	136	106
Fuel oil #6	20.6	16.0
Propane	38.7	30.1
Electricity[b]		
Off-site generation	598	465
On-site generation	33.4	26.0
On-site transportation fuel[c]		
Off-road diesel	164	67.1
Gasoline	15.3	6.25
Propane	0.942	0.386
Renewable fuel[d]		
On-site wood fuel	4320	3360
Purchased wood fuel	662	514
Total	5990	4490

[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).

Table 8. Cumulative energy (higher heating value [HHV]) consumed during production of planed (surfaced) dry lumber from the southeast compared with softwood lumber produced in the southeast and hardwood lumber produced in the northeast/north central region—cumulative, allocated gate-to-gate life-cycle inventory values (SimaPro output values).[a]

	CORRIM Phase I[b]	CORRIM Phase II[c]	
	Southeast	Northeast/ north central	Southeast
Fuel[d] (MJ/m^3)			
Wood fuel/ wood waste	3020	3720	3860
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	3940	6390	5860

[a] Includes fuel used for electricity production and for log and purchased wood fuel transportation (allocated).
[b] Consortium for Research on Renewable Industrial Materials (CORRIM) Phase I projects dealt with structural building materials in the pacific northwest and the southeast (primary producing regions).
[c] CORRIM Phase II projects dealt with structural building materials in the northeast/north central and inland west and hardwood lumber in the East.
[d] Based on HHV.

Table 8 shows cumulative energy consumption (allocated) by region and type of lumber. As expected, because of longer drying times and denser material, making hardwood lumber consumed significantly larger amounts of energy than softwood lumber. In addition, a larger value of 6.39 GJ/m^3 in the NE/NC region may contribute to energy needed to heat facilities and saw and kiln-dry frozen lumber during the winter months.

Carbon Balance

Carbon emissions are playing an increasingly important role in policy decision-making in the US 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 (Skog and Nicholson 1998), using a mixture of hardwood roundwood values for the SE. We used a mixed hardwood factor of 318 kg/m^3 of wood material and a carbon content of 53.0% with an incoming log wood mass of 1.29 OD Mg/m^3 planed dry lumber to calculate carbon balance. Average carbon input was 838 kg/m^3 of planed dry lumber with inputs in the form of logs (684 kg), bark (28 kg), and wood fuel (126 kg). Total carbon output was 847 kg/unit in the form of planed dry lumber (318 kg), coproducts (394 kg), solid emissions (18 kg), and air emissions (117 kg). Anthropogenic CO_2 was assumed to be derived from burning fossil fuels and therefore not included in the natural carbon balance. A total of 1 m^3 of planed dry hardwood lumber in the SE US stores 1.17 Mg CO_2 equivalents as a final product. Carbon stored in the final product is about nine times greater than fossil CO_2 emitted during manufacturing. As a comparison, 1 m^3 of planed dry softwood lumber from the NE/NC stores 667 kg CO_2 equivalents (Bergman and Bowe 2010a), and 1 m^3 of planed dry hardwood lumber from the NE/NC stores 1.12 Mg CO_2 equivalents (Bergman and Bowe 2008). Hardwood lumber stores larger amounts of carbon per volume mainly because of greater specific gravity (Bergman 2010).

CONCLUSIONS AND RECOMMENDATIONS

Based on LCI data developed for 12 hardwood sawmills in eight SE states, the amount of carbon stored in dry planed hardwood lumber was found to exceed fossil carbon emissions linked to manufacturing by a factor of nine. Also, carbon stored in the final product was determined to exceed all carbon emitted during manufacturing. Therefore, when hardwood lumber and its carbon stay in products held in end uses, carbon storage benefits are at their greatest.

In mills examined in this study, nearly all energy burned on-site for manufacturing hardwood lumber came from woody biomass. This was a major factor in the low average fossil emissions found for surveyed mills. Burning biomass for energy does not contribute to increasing atmospheric CO_2 provided forests are regrowing and reabsorbing the emitted CO_2 on a sustainable basis. Substituting fossil fuels for woody biomass fuel on-site during lumber manufacturing would result in additional atmospheric CO_2 emissions not being sequestered on a sustainable basis. Therefore, burning more fossil fuels during hardwood lumber manufacturing would result in greater impacts to climate change than burning woody biomass.

Sawing was found to consume the greatest proportion of electricity in the manufacturing of hardwood lumber. Thus, installing optimization equipment would lower electrical consumption by decreasing 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. Also, these features decrease electrical consumption and volume of green wood residue produced.

Drying consumed the greatest proportion of fuel. In this study, wood fuel accounted for 96% of thermal energy used and 66% of total energy consumed. Lowering overall energy consumption from upgrading or overhauling existing older and inefficient dry kiln facilities would lessen the environmental impact associated with manufacturing hardwood lumber in the SE. Also, designing and implementing new air-drying methods without loss of wood quality even in conjunction with some kiln-drying would considerably decrease the environmental impact of manufacturing hardwood lumber. Furthermore, air-drying hardwood lumber should be of a greater priority than air-drying softwood lumber because of additional drying time and energy required for drying hardwood lumber compared with softwood lumber. Air-drying lumber is a more common practice in other areas of the world in which higher moisture content for final interior wood products is typical and fuel costs are higher.

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