ENVIRONMENTAL IMPACT OF PRODUCING HARDWOOD LUMBER USING LIFE-CYCLE INVENTORY

*Richard D. Bergman**†
Graduate Research Assistant

Scott A. Bowe†
Associate Professor and Wood Products Specialist
Department of Forest and Wildlife Ecology
University of Wisconsin—Madison
120 Russell Laboratories 1630 Linden Drive
Madison, WI 53706-1598

(Received January 2008)

Abstract. Using sustainable building materials is gaining a significant presence in the US. This study examined hardwood lumber manufacturing using life-cycle inventory methodology. Material flow and energy use were identified for hardwood sawmills in northeastern US. A hardwood log volume conversion of 43.7% to planed dry lumber was found. Values of 608 MJ/m^3 of electrical and 5800 MJ/m^3 of thermal energy were determined for the manufacturing of planed dry hardwood lumber where mostly green wood residues were burned on-site for energy. Emission data produced from modeling estimated biomass and fossil CO_2 production of 428 and 139 kg/m^3, respectively. Increasing wood fuel use, a carbon-neutral process, would lower the environmental impact of hardwood lumber manufacturing and increase its use as a green building material.

Keywords: Environmental impact, hardwood lumber, life-cycle inventory, CORRIM, LCI, green material.

INTRODUCTION

Hardwood lumber is used primarily in wood flooring, pallets, furniture, cabinets, and moulding. In 2005, the total annual hardwood production for the US was 25.0 million m^3 (USCB 2006a). Most hardwood lumber is consumed domestically, but there was an estimated 3.19 million m^3 exported in 2005 (HMR 2006). Domestic hardwood lumber production occurs mostly in the eastern US, with an annual production of 24.1 million m^3 split equally between the northeastern and southeastern states. A small percentage of hardwood lumber production occurs on the West Coast.

Economic costs, energy use, and environmental impact of residential building products are playing an increasing role due to increased awareness of the public of environmental issues. Two major reasons for the increase in residential building are the increase in average size and the number of US new single-family residential housing units. The average-size single-family residential home has increased from 193 m^2 in 1991 to 226 m^2 in 2005, and completed single-family residential units have roughly increased 100% to 1.64 million units during this same period (USCB 2006b).

"Green building" is defined as the practice of improving energy efficiency for materials, construction, and operation while reducing the overall environmental impact of building. Two percent ($7.4 billion) of new residential starts in 2005 were classified as "green buildings", and the minimum market share is expected to increase to 5% ($19 billion) by 2010 (MHC 2006). Developing a sound policy for building practices, especially for green buildings, must be a priority if the US is to decrease its environmen-

---

* Corresponding author: rbergman@wisc.edu
† SWST Member

Wood and Fiber Science, 40(3), 2008, pp. 448–458

tal burden on the world's resources. However, scientific evidence is needed to evaluate claims for green building materials.

Providing accurate baseline data for hardwood lumber production through a gate-to-gate Life-Cycle Inventory (LCI) is part of sustainable practices regarding building styles, construction materials, product improvements for energy consumption, and carbon sequestration policies. This LCI study provides data for examining the environmental impact of hardwood lumber production. In addition, these data can be interconnected into the scientific database managed by the National Renewable Energy Laboratory to complete a Life-Cycle Analysis (LCA) of hardwood lumber-related wood products (NREL 2007). Hardwood lumber is the raw material used in producing hardwood flooring, moulding, and other millwork that are considered building materials unlike hardwood lumber.

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 tracks hardwood lumber production from hardwood logs stored in the log yard to planed dry lumber. 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. Such a cradle-to-grave assessment is beyond the scope of this study.

Rough green lumber sawn from hardwood logs is typically dried in conventional dry kilns using wood and fossil fuels as heat sources. It is estimated that more than 90% of all hardwood lumber dried in the US uses wood residues from the milling processes as fuel (Denig et al 2000). Prior to drying the lumber, boards are stickered and stacked to aid drying and prevent drying defects. The drying process consumes roughly 70–80% of the "total" energy required for producing hardwood lumber (Comstock 1975). The sawing process consumes the highest percentage of "electrical" energy. Total energy is comprised of both electrical and thermal. The rough dry lumber is planed to standard grade thicknesses when drying is complete.

The goal of this study was to document the LCI of planed dry lumber production from hardwood logs and determine the material flow, energy use, and emissions for the hardwood lumber manufacturing process on a per unit basis for the northeastern US (Fig 1). Primary data were collected through questionnaires mailed to 20 lumber mills, while secondary data were collected from peer-reviewed literature per Consortium for Research on Renewable Industrial Material (CORRIM) guidelines (CORRIM 2001). There

FIGURE 1. Region selected (dark area) for LCI of hardwood lumber production in the US.

are a large number of commercial hardwood species sawn in the northeastern US. Table 1 shows the breakdown of species data for the 20 mills and their location by state.

Material and energy balances were calculated from these primary and secondary data sources. Using these values, the environmental impact was found from modeling the emissions through software called SimaPro 7 (PRé Consultants 2007), which follows the ISO 14040 protocols. SimaPro was used in previous CORRIM-initiated LCI projects: softwood lumber (Milota et al 2005), softwood plywood (Wilson and Sakimoto 2005), I-joist production (Wilson and Dancer 2005a), glue-laminated timbers (Puettmann and Wilson 2005), and laminated veneer lumber (Wilson and Dancer 2005b).

PROCEDURE

Hardwood Lumber Manufacturing and the Four Main Unit Processes

Production of hardwood lumber starts with hardwood logs that are typically trucked to the sawmill, scaled, graded, and stored in the log yard until sawn. Logs may be stored wet or dry depending on species and season. There are four main unit processes in producing hardwood lumber: sawing, drying, energy generation, and planing (Fig 2). In the sawing process, the hardwood logs are sawn into mostly 28.6-mm-thick rough green lumber of random width and 2.44-m lengths. The sawing process uses the most electrical consumption of all unit processes. Once the rough green lumber is scaled (to measure production volume) and stickered, the lumber is typically dried to 6–8% moisture content on an oven-dry basis (MC_{DB}) using generally energy-intensive drying methods. After drying, the rough dry lumber is planed to the required dimensions. Energy for these material processes comes from the energy generation process in addition to fuels and electricity purchased from off-site sources.

Sawing. This unit process begins with logs in the mill yard and ends with sawn rough green lumber and wood residue from the sawing process: bark, sawdust, slabs, edgings, and chips

TABLE 1. *Participating mill characteristics.*

	Species mix[1] by percentage												
Mill	RO (mix)	HM	SM	WO (mix)	YP	BC	Ash (mix)	BW	Birch (mix)	Basswood	Hickory	Other	Location by state
A	7.0	26.0	20.0	2.0	5.0	8.0	8.0	—	—	5.0	9.0	10.0	NY
B	48.4	—	—	28.0	27.6	—	—	—	—	—	—	—	NY
C	30.6	38.4	3.1	—	—	2.8	11.2	—	9.6	—	—	4.3	VT
D	19.0	37.0	12.0	4.0	—	18.0	6.0	—	—	—	—	4.0	PA
E	19.0	16.0	21.0	9.0	—	23.0	7.0	—	—	—	—	5.0	PA
F	58.0	7.0	—	15.0	10.0	2.0	5.0	—	—	—	—	3.0	MO
G	24.2	8.0	2.0	4.7	34.0	4.0	5.4	9.1	—	1.6	6.7	0.3	IN
H	25.0	21.0	—	15.0	—	—	5.0	13.0	—	7.0	—	14.0	IA
I	25.0	50.0	5.0	—	—	—	—	—	20.0	—	—	—	ME
J	11.0	56.0	13.0	—	—	3.0	1.0	—	1.0	14.0	—	1.0	WI
K	36.0	7.0	8.0	20.0	12.0	5.0	5.0	—	—	—	—	7.0	PA
L	5.0	47.0	—	—	—	—	5.0	—	6.0	14.0	—	23.0	WI
M	12.0	15.0	—	17.0	—	8.0	7.0	12.0	—	—	—	29.0	IN
N	15.0	10.0	—	17.0	15.0	—	7.0	13.0	—	—	—	23.0	IN
O	35.0	—	—	5.0	60.0	—	—	—	—	—	—	—	PA
P	51.0	7.0	3.0	18.0	—	3.0	2.0	—	—	6.0	3.0	7.0	WI
Q	40.0	15.5	5.4	5.0	16.8	—	9.3	—	—	—	—	8.0	OH
R	15.2	—	—	39.5	7.7	16.5	8.0	—	—	—	—	13.1	OH
S	20.0	3.3	5.9	5.3	44.5	13.7	—	—	—	—	—	7.3	WV
T	50.3	—	—	25.0	22.0	—	—	—	—	—	—	—	NY
TOTAL	27.7	16.3	4.7	8.7	20.8	5.0	3.8	1.5	1.9	2.1	1.1	6.2	

[1] RO: red oak, HM: hard maple, SM: soft maple, WO: white oak, YP: yellow poplar, BC: black cherry, BW: black walnut.

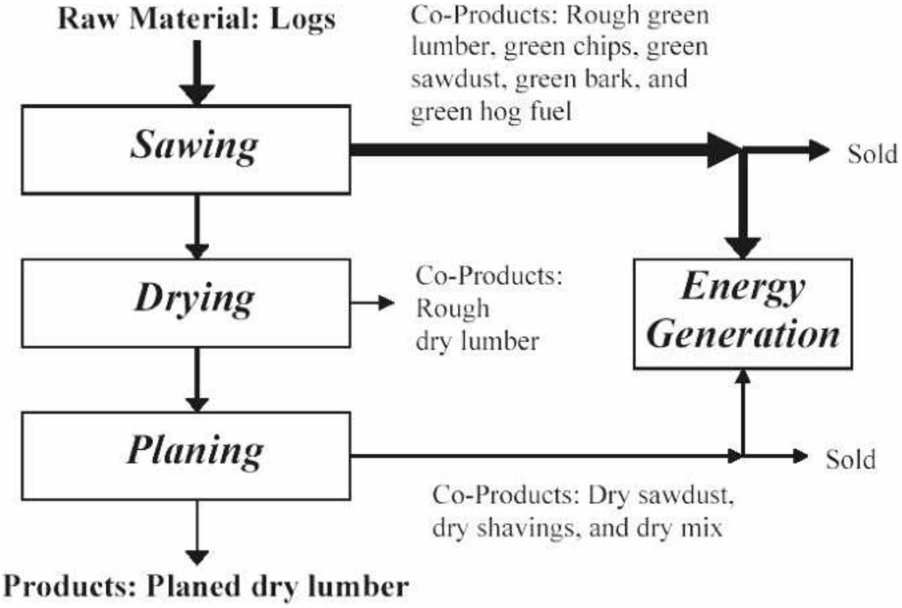

FIGURE 2. Description of the four unit processes for hardwood lumber manufacturing showing material flow.

(hog fuel, another category, is a mixture of the wood residue produced). Most wood residue is sold as a coproduct, while some residue, especially sawdust, is combusted on-site as fuel to mostly kiln dry the lumber. The remaining wood residue produces salable goods such as mulch, paper chips, feedstock for particleboard plants, etc.

Drying. This unit process begins with rough green lumber and ends with rough dry lumber going to the planer mill. Drying generates most of the volatile organic compounds (VOC) generated on-site and uses the most energy produced on-site from wood and fossil fuel combustion. Different drying methods are used depending on species, lumber thickness, lumber grade, and available wood residue markets.

Energy generation. This unit 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 wood residue from the sawing process generates most of the thermal energy used at the plant. The second energy source used on-site is off-site grid electricity. The outputs of this unit process are steam and hot water from boilers, combustion gases for drying, electricity from cogeneration units, solid waste (wood ash), and air emissions (eg CO_2 and CO) from combustion.

Planing. This unit process begins with stickered, rough kiln-dried lumber, and produces surfaced and packaged lumber, sorted by type, size, and grade, as well as planer shavings, sawdust, and lumber trim ends (dry wood residue). This process is the final stage of manufacturing. Some dry wood residue is combusted on-site for energy while most is sold as coproducts. Some planed lumber is only skip (hit or miss) planed from 25.4 mm to 23.8 mm instead of the standard 20.6 mm for 4/4 hardwood lumber. Secondary manufacturers, such as hardwood flooring companies, also plane a significant portion of rough dry lumber. Furthermore, rough dry lumber is not precision end-trimmed.

Functional Unit

For this study, material flows, energy use, and emission data are standardized to a per unit volume basis of 1.0 m^3 planed dry lumber, ie the final product of the hardwood lumber manufacturing process. Hardwood lumber is produced in random width and can vary in the planed dry thickness; in this LCI study, 1 × 6 boards were assumed to represent the average production and were assigned a 140-mm width and 20.6-mm thickness (FPL 1999). Rough green lumber and rough dry lumber were assumed to be 28.6 mm by 144 mm and 27.0 by 143 mm, respectively, and board length was 2.49 m prior to planing. Allocating all material and energy on a per unit basis of 1.0 m^3 planed dry lumber standardized the results to meet ISO protocols and can be used for other CORRIM studies including future LCA studies (ISO 1998; ISO 2006; CORRIM 2001).

System Boundaries

Boundary selection is important because the material and energy that cross this boundary need to be accounted for (Fig 3) through the gate-to-gate LCI. There are two boundaries as defined by CORRIM (Wilson and Sakimoto 2005) used to track the environmental impact of hardwood lumber production. One is the total (cumulative) system boundary (solid line in Fig 3) that includes both on- and off-site emissions for all material and energy consumed. The site system boundary (dotted line in Fig 3) is the environmental impact for emissions developed just at the hardwood sawmill (ie on-site) from the four unit processes. Examples of off-site emissions are grid electricity production, transportation of logs and lumber to and from the mill, and fuels produced off-site but used on-site.

Assumptions

Bergman and Bowe (2007) provided detailed assumptions used to determine the results for this LCI study.

RESULTS

Material Flow

Mass and energy values including emissions for hardwood lumber production were found by surveying the 20 mills in the northeastern US with detailed questionnaires on mass flow and energy consumption. The survey data were modeled in SimaPro 7 to find nonwood raw material use and emission data.

All energy and material values were weight averaged from the 20 mills across 20 states in the northeastern US (Fig 3). For the 20 mills, 784,000 m^3 rough green lumber was produced in

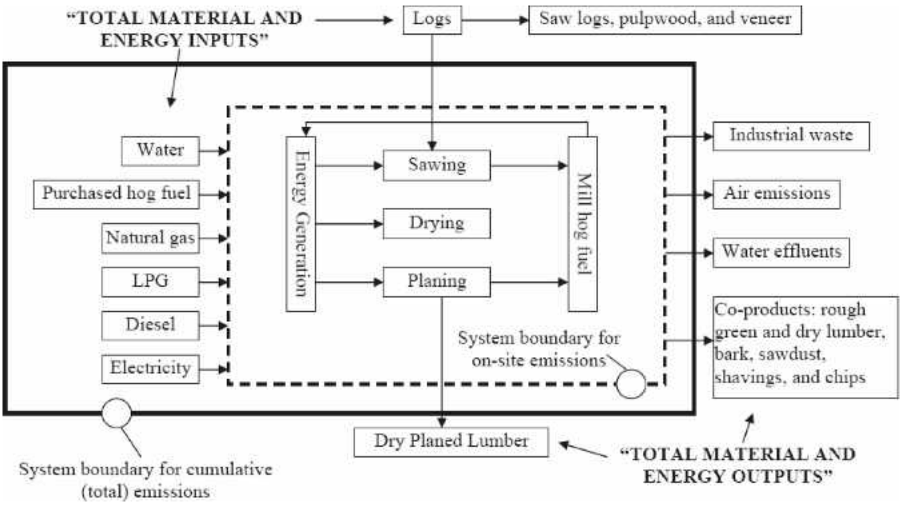

FIGURE 3. System boundaries for hardwood lumber production.

2005 out of a total production from this region of 12.0 million m^3. This value is roughly 6.5% (USCB 2006a) of the total production for 2005. A minimum of 5% is required for data quality (CORRIM 2001). Also, 432,000 m^3 and 229,000 m^{3}of rough dry lumber and planed dry lumber, respectively, were produced from this 784,000 m^3 of rough green lumber.

For the mass balance, 1170 oven-dried (OD) kg of incoming hardwood logs with a green specific gravity (OD mass/green volume) of 0.511 produced 1.0 m^3 of planed dry lumber (Table 2). Sawing produced 712 OD kg of rough green lumber; the drying process did not result in any loss of wood substance. Planing reduced the 712 OD kg of rough dry lumber to 535 OD kg of planed dry lumber for a 25% reduction in mass. Overall, the log was reduced to 45.8% of its original mass to produce the final product of planed dry lumber.

Mills are concerned with their lumber recovery factor. Therefore the volume reduction was determined. Most mills in the US use nominal volumetric values such as board feet to purchase and sell their products. In the northeastern region of the US, 2.29 m^3 of hardwood logs are sawn into 1.46 m^3 of rough green lumber, dried to 1.37 m^3 of rough dry lumber. Planing the rough dry lumber produces 1.0 m^3 of planed dry lumber for a total volume conversion of 43.7% from incoming logs.

Energy Consumption

Hardwood lumber production requires both electrical and thermal energy for processing logs into planed dry lumber. All of the thermal energy is produced on-site while most electricity (grid electricity) is produced off-site. Electrical energy is required by all four unit processes while most thermal energy is required by the drying process. Total electrical consumption was 608 MJ/m^3 planed dry lumber. This includes both off-site and on-site electrical sources (Table 3). The unit processes (sawing, drying, energy generation (boiler operation), and planing) consume 50, 25, 5, and 20% of the total, respectively. Based on these percentages, the four unit processes used 304, 152, 31, and 121 MJ/m^3 planed dry lumber. Thermal energy contributes a significantly higher fraction of total energy.

Manufacturing planed dry lumber required 5.8 GJ/m^3 of thermal energy. The thermal energy required for drying and other associated drying processes including walnut steaming, cogeneration, and facility heating is based on fuel consumption with the major source being wood fuel produced on-site from the sawing process. A

Table 2. *Overall wood mass balance for production of a per unit basis of planed dry lumber.*

Material (oven-dried kg)[1]	Sawing process		Boiler process	Drying process		Planer process		All processes combined		
	Input	Output	Input	Input	Output	Input	Output	Input	Output	Diff
Green logs	1170							1170	0	−1176
Green chips		227	30.3					30	227	196
Green sawdust		189	140					140	189	49
Green bark[2]	131	139	0.5					132	139	7.9
Green hog fuel		45	18.4					18	45	26
Rough green lumber		712		712				712	712	0
Rough dry lumber					712	712		712	712	0
Planed dry lumber							535	0	535	535
Dry shavings			0				86	0	86	86
Dry sawdust			27.4				46	27	46	19
Dry mixings			0				44	0	44	44
Sum	1301	1311	217	712	712	712	712	2941	2735	−206[3]

[1] Values given in oven-dry mass.

[2] Bark volume is not included in log scale.

[3] The total in the last column corresponds to the amount of wood fuel generated and consumed on-site.

TABLE 3. *Material and energy consumed on-site to produce a cubic meter of planed dry lumber.*

Fuel type	Quantity/m^3	
Fossil fuel[1]		
Natural gas	16.4	m^3
Fuel oil #2	2.08	L
Propane	1.21	L
Electricity[2]		
Off-site generation	597	MJ
On-site generation	10.2	MJ
On-Site transportation fuel[3]		
Off-road diesel	6.57	L
Propane	0.267	L
Gasoline	0.571	L
Renewable fuel[4]		
On-site wood fuel	217	kg
Purchased wood fuel	35.4	kg
Water use		
Municipal water	—	L
Ground water	244	L

[1] Energy values were found using their higher heating values (HHV) in MJ/kg: 54.4 for natural gas, 43.3 for fuel oil #1 and #2, 45.5 for fuel oil #6, and 54.0 for propane (LPG).

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

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

[4] Values given in oven-dried mass (20.9 MJ per OD kg).

portion of wood fuel produced on-site, 217 OD kg, and some purchased wood fuel, 35.4 OD kg, is combusted to generate heat per 1.0 m^3 planed dry lumber for the mill. Thermal energy produced on-site makes up the largest proportion of energy used on-site. Overall, wood fuel composed 87% of total energy consumed on-site, with the next largest contributor being natural gas at 11%. Propane and fuel oil play a minor role compared with these other fuels. Coal was the largest source of energy used off-site (beyond the mill's boundary) because most grid electricity in the northeastern US is generated from coal power plants.

On-site transportation of wood stock is a major fuel consumer with off-road diesel having the highest consumption. Propane and natural gas are also used for forklifts, front-end loaders, trucks, and other equipment used within the system boundary of the facility. Off-road diesel consumption was 6.57 L/m^3 of planed dry lumber and was consumed at 10 times the rate of either propane or gasoline on average. On-site transportation fuel consumption is broken down for the unit processes into the following percentages: 60, 10, 10, and 20% for sawing, drying, energy generation, and planing, respectively. The corresponding values of the four processes for off-road diesel were 3.94, 0.66, 0.66, and 1.31 L, respectively.

The location of the hardwood lumber facility affects the environmental impact since most electricity used is from the electric power industry. The Pacific Northwest region produces most of their electricity from hydro (Milota et al 2005). Average composition of (off-site) electrical generation was found for the Northeast by totaling the amount of the different fuel sources for each of the 20 states given in 1000 kWh and calculating the percentages (USDOE 2006). The most significant electric power contributor in the northeastern region is coal with 58.0% 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 23.7, 10.3, 3.4, 2.7, and 1.9%, respectively.

Environmental Impact

SimaPro 7 gave output factors allocated to just manufacturing of dry planed lumber, not to the associated wood coproducts. Outside of the logs processed to lumber, the major consumption of raw materials was due to electrical generation and purchased fuel. Purchased wood fuel, coal, and natural gas were some of the largest contributors with the values of 26.6, 35.3, and 14.4 kg, respectively allocated for manufacturing 1.0 m^3 planed dry lumber (Table 4). Most of the coal and natural gas was used to produce off-site electricity and some for producing transportation fuel used on-site. The region selected for production affects the environmental impact of hardwood lumber production because coal is the off-site material used most for electrical power generation in the Northeast, whereas most power in the Pacific Northwest is produced from hydro and then natural gas.

Actual emission rates from facilities can be used to determine regulatory policies. CO_2 and par-

TABLE 4. *Raw materials consumed during production of a per unit basis of planed dry lumber.*

Raw material	Quantity[1]/m^3	
Wood, unspecified, standing[2]	1.43	m^3
Water, well, in ground[4]	0.15	m^3
Purchased wood and wood waste	26.2	kg
Coal, in ground[4]	35.3	kg
Gas, natural, in ground[4]	14.4	kg
Oil, crude, in ground[4]	8.16	kg
Limestone, in ground[4]	5.34	kg
Uranium, in ground[4]	0.00093	kg

[1] 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.

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

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

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

ticulates are typically measured although other emissions are frequently monitored to ensure compliance. CO_2 emissions are separated into two fuel sources, biogenic (biomass-derived) and anthropogenic (fossil fuel-derived). Biogenic CO_2 is 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. Using a 12% MC specific gravity (OD mass/12% MC volume) of 0.561, emission values of 428 and 139 kg were reported from SimaPro for biogenic and anthropogenic CO_2, respectively (Table 5). Research into measuring volatile organic gases (VOC) produced from drying lumber generated the value of 1.20 kg/m^3 and is species, temperature, and moisture dependent with the highest VOC emissions from red oak (Rice and Erich 2006).

TABLE 5. *LCI 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)	9.62E-04	1.62E-04
Cl$^-$	4.05E-02	1.01E-03
Suspended solids	6.96E-02	1.12E-02
Oils	1.58E-02	6.42E-04
Dissolved solids	8.90E-01	3.75E-02
Chemical Oxygen Demand (COD)	1.28E-02	5.78E-03
Soil emissions		
Waste in inert landfill	7.53E+00	7.53E+00
Waste to recycling	2.24E-01	2.24E-01
Solid waste	3.57E+01	1.72E+01
Air emissions		
CO	3.13E+00	2.84E+00
CO_2 (biomass)	4.28E+02	3.98E+02
CO_2 (fossil)	1.39E+02	4.65E+01
CH_4	2.73E-01	3.96E-03
Non-methane, volatile organic compounds (NMVOC)	2.32E-01	6.87E-02
NOx	1.02E+00	6.37E-01
Particulate (total)	1.16E+00	1.16E+00
Particulate (PM10)	7.35E-02	5.33E-02
Particulate (unspecified)	9.05E-02	1.40E-03
Sox	1.15E+00	7.46E-02
VOC	1.20E+00	1.20E+00

Carbon Balance

Carbon emissions play 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 such as Skog and Nicholson (1998) using a mixture of hardwood roundwood values for the northcentral and northeastern US. Carbon input was 914 kg/m^3 plane dried lumber with the following carbon sources in kg: 670 from logs, 75 from bark, and 170 from wood fuel. The total carbon output was 908 kg per unit basis with the following carbon sources in kg: 306 from planed dry lumber, 444 from coproducts, and 157 from air emissions. This resulted in a percentage difference of 0.71% between the total carbon input and output.

Summary of Results

A rigorous material and energy balance was completed on the 20 hardwood mills. The results indicate that total energy consumption varied significantly, depending on the species sawn, age of the boiler and dry kiln equipment, and method of drying. For hardwood lumber, an average thermal consumption of 5800 MJ/m^3 of planed dry lumber and electrical energy consumption of 608 MJ/m^3 of planed dry lumber were found. Two mills produced their own electrical power from the wood residue produced on-site and consumed about four times the amount of wood residue than mills that did not produce their electrical power.

Electrical consumption varied significantly, depending on whether the mill used conventional steam kilns, dehumidification kilns, predryers, or air yards to dry lumber. Two mills using dehumidification kilns consumed 45.3% more electrical energy compared with the other mills, although dehumidification kilns used less than 5% of the average thermal energy. Most mills producing red and white oak lumber used predryers and air yards to lower moisture content prior to kiln drying to reduce time in the kilns. Mills running predryers used 64.5% more electricity than did the average mill.

Thermal energy use also varied considerably, depending on whether the mill ran a walnut steamer or a cogeneration unit. Four mills operated walnut steamers. Thermal energy was reduced by 45.3% for on-site wood fuel use from 151 to 83 OD kg/m^3 planed dry lumber when the mills steaming walnut and producing on-site electricity were not used in calculations. This is significant because wood fuel produced on-site provides about 74% of the total thermal energy required.

Softwood lumber consumes less electrical and thermal energy in production (Milota et al 2005) compared with hardwood lumber (Table 6). There are several reasons for this. One reason is that hardwood lumber requires longer drying times to prevent lumber degrade. Also, more thermal energy is consumed because of the higher amount of water in hardwoods, due to their typical higher density than softwoods, for the same volume of product (Simpson 1991). Another reason is that hardwood logs are more likely to be converted to high-grade lumber. Also, hardwoods are typically dried to a lower final MC of 6 to 8% compared with 15 to 19% MC_{DB} for softwoods. As stated, hardwoods are generally denser than softwood lumber, and since hardwood lumber is typically sawn to thinner dimensions, more electrical energy is consumed in the sawing process (more kerfs are required to break down the log into lumber). In this study, the Northeast used more energy also to keep the facility heated during winter months compared with the Pacific Northwest and Southeast, the primary regions for softwood lumber production.

Table 6. *Comparison of hardwood to softwood lumber energy use.*

	Overall energy consumption	
	Electrical energy (MJ/m^3)	Thermal energy (MJ/m^3)
Hardwood lumber[1]	597	5,400
Softwood lumber[2]	335	3,600

[1] Includes walnut steaming, cogeneration, and plant heating.

[2] 1.623 m^3 per 1.0 nominal MBF (thousand board feet of 2 × 6 boards) planed dry softwood lumber; 3.6 MJ per kWh, 1054 MJ per million BTU.

DISCUSSION

Total energy consumption per cubic meter of planed dry hardwood lumber was found to be comparable to published data (Armstrong and Brock 1989; Comstock 1975). However, unlike previous studies, processes such as walnut steaming, facility heating, and cogeneration were examined because their energy use was significant. Wood has two significant advantages over nonwood substitutes; wood is carbon-neutral and carbon can be sequestered. Therefore, using wood as a fuel or in a finished wood product from hardwood lumber could be considered a sustainable practice. Other nonwood 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. The most energy efficient method would be upgrading or refurbishing the mill's aging dry kiln facilities at mills currently using more than 1.5 times the amount of energy per m^3 as compared with the mill using similar drying technology with similar species composition. This may also improve lumber quality because the newer dry kilns will probably have greater precision in maintaining kiln temperatures and air velocities. Sawing lumber manually (without computer assistance) may increase sawing errors, and thus sawing time and electrical costs. Using improved sawing practices such as the Best Opening Face program (Harpole and Hallock 1977) and thinner saw kerfs has increased lumber yields while lowering electricity consumption.

Another approach reduces thermal energy use. Several different drying methods 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 due to drying degrade and large quantity of drying stock required. Maintaining a large lumber inventory for air drying reduces profits due to delays in recovering investments. Air drying lumber has the lowest control among the different drying methods, resulting in the highest level of degrade although it provides the lowest energy use of all drying methods. Other methods such as progressive dry kilns for softwood lumber drying could be redesigned for hardwood lumber (FPL 1999; Denig et al 2000).

CONCLUSIONS

Based on the LCI results, the following conclusions are drawn:

- Sawing consumes the highest proportion of electricity in the manufacturing of hardwood lumber. Thus, installing optimization equipment would lower electrical consumption by reducing sawing errors. Thinner saws reduce electrical consumption and reduce volume of green wood residue produced.
- Drying consumes the highest proportion of fuel. In this LCI study, wood fuel accounted for 87% of thermal energy used. Lowering overall energy consumption by upgrading or overhauling existing older and inefficient dry kiln facilities is indicated. Redesigning progressive dry kiln commonly used in the Scandinavian countries for softwood lumber would also significantly reduce energy consumption for mills drying large volumes of the same species and thickness of hardwood lumber.
- Increasing on-site wood fuel consumption would reduce fossil greenhouse gases but increase other products such as particulate emissions. Particulate emissions may be reduced by reinjecting fly ash.
- Region of the production affects the environmental impact of this product because coal is largest off-site material used for electrical power generation in the Northeast. Most power in the Pacific Northwest is produced from hydro and then natural gas, while most power in the Southeast is produced from coal and uranium just like the Northeast.
- 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 with nonwood 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 subfloor, since floors and carpeting are measured in surface area in the US. This study gives all values based on a cubic meter on an oven-dried mass; therefore, thickness of material is a critical dimension for consideration. Also, there are databases available besides the NREL LCI Database that may not have used the same methodology. One such database is from the National Institute of Standards and Technology that developed the Building for Environmental and Economic Sustainability database and software.

Caution must be used when comparing studies using different boundaries and methods (NIST 2003; BEES 2007).

ACKNOWLEDGMENTS

Thanks to James B. Wilson and Maureen E. Puettmann, Oregon State University, for help on technical aspects of LCI analysis, and Susan Regan and the Hardwood Manufacturing Association for their invaluable assistance in gathering the mill data. Financial assistance provided for this research project by the USDA Forest Service, Forest Products Laboratory (JV1111169-211) through CORRIM and the USDOE is gratefully acknowledged. The authors also thank Professor KT. Hartwig, Melissa Kershner, and Samuel Zelinka for their review comments on this paper.

REFERENCES

Armstrong JP, Brock SM (1989) Predicting fuel consumption of central Appalachian kiln-drying enterprises. Forest Prod J 39(3):57–61.

BEES (2007) Building for Environmental and Economic Sustainability. National Institute of Standards and Technology Building for Environmental and Economic Sustainability (BEES) Model (version 4.0). http://www.bfrl.nist.gov/oae/software/bees/

Bergman RD, Bowe SA (2007) Life-Cycle Inventory of Hardwood Lumber Manufacturing in the Northeastern and Northcentral United States. CORRIM Phase II Final Report. University of Washington, Seattle, WA. 53 pp.

Comstock GL (1975) Energy requirements for drying of wood products. *In*: Wood residues as an energy source. Forest Products Research Society, Madison, WI. Pp 8–12.

CORRIM (2001) Research Guidelines for Life-cycle Inventories. Consortium for Research on Renewable Industrial Materials. CORRIM, Inc. University of Washington, Seattle, WA. April. 47 pp.

Denig J, Wengert EM, Simpson WT (2000) Drying hardwood lumber. Gen Tech Rep FPL-GTR-118. USDA Forest Service, Forest Prod Lab, Madison, WI. 138 pp.

FPL (1999) Wood handbook: Wood as an engineering material. Gen Tech Rep FPL-GTR-113 USDA Forest Service, Forest Prod Lab, Madison, WI. 463 pp.

HMR (2006) Hardwood Market Report. 2005: The year at a glance. 9th annual statistical analysis of the North American hardwood marketplace. Memphis, TN. 168 pp.

Harpole GB, Hallock H (1977) Investment opportunity: Best opening face sawing. Res. Pap. FPL-RP-291. USDA Forest Service, Forest Prod Lab, Madison, WI. 9 pp.

ISO (1998) Environmental management—life-cycle assessment—goal and scope definition and inventory analysis. International Organization for Standardization. ISO 14041. First Edition 1998-10-01. Geneva, Switzerland. 26 pp.

——— (2006) Environmental management—life-cycle assessment—Requirements and guidelines. International Organization for Standardization. ISO 14044. International Standard. Geneva, Switzerland. 46 pp.

MHC (2006) Green building smartmarket report. McGraw Hill Construction. New York. HD9715.U5 G69. 44 pp.

Milota MR, West CD, Hartley ID (2005) Gate-to-gate life inventory of softwood lumber production. Wood Fiber Sci 37(CORRIM Special Issue):47–57.

NIST (2003) Interior flooring life-cycle inventory data. National Institute of Standards and Technology. http://www.nist.gov/ (27 Nov 2007).

NREL (2007) Life-cycle inventory database project. National Renewable Energy Laboratory. http://www.nrel.gov/lci/. (27 Feb 2007).

Peuttmann ME, Wilson JB (2005) Gate-to-gate life-cycle inventory of glue-laminated timbers production. Wood Fiber Sci 37(CORRIM Special Issue):99–113.

Pré Consultants (2007) SimaPro7 life-cycle assessment software package, Version 7.0.2. Plotter 12, 3821 BB Amersfoort, The Netherlands. http://www.pre.nl/. (27 Feb 07).

Rice RW, Erich MS (2006) Estimated VOC losses during the drying of six eastern hardwood species. Forest Prod J 56(10):48–51.

Simpson WT (1991) Dry kiln operator's manual. Agric. Handbook AH-188. Madison, WI: USDA Forest Service, Forest Products Laboratory. 274 pp.

Skog KE, Nicholson GA (1998) Carbon cycling through wood products: The role of wood and paper products in carbon sequestration. Forest Prod J 48(7/8):75–83.

USDOE (2006) Net Generation by Energy Source by Type of Producer. United States Department of Energy. http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls (15 January 2007).

USCB (2006a) Lumber Production and Mill Stocks: 2005. US Census Bureau http://www.census.gov/industry/1/ma321t05.pdf (10 October 2006).

——— (2006b) New Residential Construction Index: 2006. US Census Bureau. http://www.census.gov/const/www/newresconstindex.html (19 March 2007).

Wilson JB, Sakimoto ET (2005) Gate-to-gate life-cycle inventory of softwood plywood production. Wood Fiber Sci 37(CORRIM Special Issue): 58–73.

———, Dancer ER (2005a) Gate-to-gate life-cycle inventory of I-joist production. Wood Fiber Sci 37(CORRIM Special Issue):85–98.

———, ——— (2005b) Gate-to-gate life-cycle inventory of laminated veneer plywood production. Wood Fiber Sci 37(CORRIM Special Issue):114–127.