GATE-TO-GATE LIFE-CYCLE INVENTORY OF SOFTWOOD LUMBER PRODUCTION

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ABSTRACT

To perform a life-cycle analysis, a life-cycle inventory is needed. Data from surveys of manufacturers are presented for the energy and materials required to produce 1.623 m^3 (1 mbf) of planed, dry, dimension lumber from logs in the western and southern U.S. In the West and South, 53 and 41% of the log volume (3.05 and 3.92 m^3) leaves the mill as planed, dry dimension lumber, respectively. A much greater portion of the energy used for production in the South is produced on site from wood fuels. CO_2 emissions were greater in the South because of the wood fuel, 574 kg versus 419 kg per 1.623 m^3 produced.

Keywords: Dimension lumber, life-cycle, energy, CO_2, southern pine, Douglas-fir, western hemlock.

INTRODUCTION

Wood is claimed by industry to be environmentally friendly, energy efficient, and aesthetically pleasing compared to competing materials such as steel, concrete, and plastic. Environmental claims are based on the fact that wood is a renewable resource, a carbon storage medium, and is produced by nature in the forest while providing recreation, water, and clean air. It is also claimed that wood requires low production energy and causes few pollutants. In service, energy benefits are claimed based on the relatively high insulation value of wood in a structure. Claims of easy recycling are also made.

The objective of this work is to determine energy and material inputs and outputs associated with the production of planed dry lumber, the main framing material for housing in North America, from logs. These data are needed for the inclusion of the production process in life-cycle analyses of wood. The data were obtained through a scientifically sound and consistent process established by the Consortium for Research on Renewable Industrial Materials (CORRIM), which follows ISO 14041 protocols. CORRIM is developing a database for the environmental impacts of processing and using wood and wood-based materials from generation, through use and disposal.

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The scope of this study includes gate-to-gate life-cycle inventories (LCIs) based on primary data for producing planed, dry dimension (framing or construction) lumber from logs using practices and technology common to the western and southern United States. These LCIs are intended for use in life-cycle assessment of wood as a building material. This paper is based on CORRIM reports (Milota 2004; Milota et al. 2004), which contain additional details.

Much of the past life-cycle inventory and assessment of wood has dealt with it as a fuel rather than a construction material (Jungmeier et al. 2003). For fuel, the embodied energy is an important consideration, especially if the trees are grown and harvested specifically for bioenergy. Keoleian et al. (2001) cite the energy content of wood as 17.7 MJ/kg and the processing energy for lumber as 10.7 MJ/kg (4.8 GJ/m^3 assuming a density of 450 kg/m^3) of which 5.8 MJ/kg comes from renewable sources (biomass). The energy content is in reasonable agreement with values in Wilén et al. (1996), 20.89 MJ/kg for chips and 19.83 to 20.95 MJ/kg for bark.

Trees for lumber production are primarily grown and harvested for use as a material. The renewable energy cited by Keoleian et al. (2001) results from the on-site combustion of portions of the tree not used for lumber, chips, or other higher valued products. This energy is often used for drying the lumber. Jungmeier et al. (2002a) indicated that for a bioenergy plant, the life-cycle assessment should include the infrastructure; however, this may be neglected for wood used as a material.

Jungmeier et al. (2002b) present several scenarios for LCA on a sawmill complex. They indicate that it can be treated as one process unit if the sawn lumber receives 100% allocation. The co-products, however, leave the process at different stages, and if they share the allocation, then the sawmill complex must be divided into smaller process units.

Procedure

The product studied is planed, dry dimension lumber produced from logs. It is intended for framing wooden buildings. Dimension lumber is nominally 2-inches thick by 4- to 12-inches wide (actual dimensions are 38 mm by 89 to 305 mm). The product forms the basis for the functional unit for this LCI, 1.623 m^3 of planed, dry dimension lumber, or 1000 board feet (1 mbf), the common unit for commerce in North America. For western production, the survey is for dimension lumber produced in the states of Oregon and Washington, west of the Cascade mountains. For southern production, the survey region is the states of Georgia, Alabama, Mississippi, and Louisiana. Annual lumber production in the region for Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) is approximately 21 million cubic meters, 70% of which is dimension lumber. A small amount of true fir (*Abies* spp.) may also be included with the western hemlock. Annual production of southern pine dimension lumber is approximately 36 million cubic meters. Southern pine is used to describe a collection of several pine species (Panshin and de Zeeuw 1980), typically, longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*P. echinata*. Mill.), loblolly pine (*P. taeda* L.), and slash pine (*P. elliottii* Engelm.).

The process system for this LCI is a sawmill complex that produces planed, kiln-dried dimension lumber. The system boundary begins with logs delivered to the sawmill complex and ends with planed dry lumber and other co-products leaving. The sawmill complex was divided into four process units: sawing, drying, energy generation, and planing (Fig. 1). This breakdown is necessary to avoid inappropriate allocation because some co-products leave the mill prior to drying, the unit process with the most significant environmental load.

Sawing encompasses log storage and the breakdown of the logs into rough green lumber. Drying encompasses the kilns, loading area, and unloading/cooling areas. Planing encompasses the unstacker, planer, and packaging areas. Each of these includes conveyance to the next unit process or plant gate. Energy generation encompasses fuel storage, the boiler, and steam distribution system. Both wood-fired and natural gas boilers are used, plus a small amount of diesel.

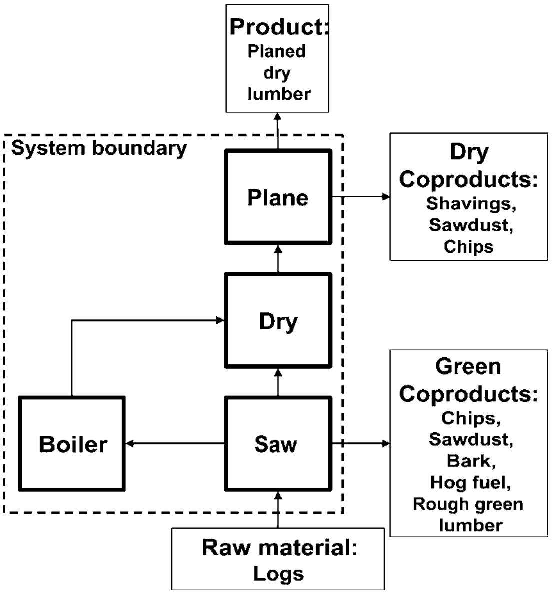

FIG. 1. Flow diagram for lumber production. Bold borders indicate the four unit processes. Dashed line indicates system boundary. Only wood materials are shown for clarity. Other materials and fuels also cross system boundary.

Co-generation of electricity sometimes occurs. Chips are used to make paper or composite wood products. Bark is used for landscaping material or fuel. Hog fuel is used for fuel. Sawdust and planar shavings are used in composite wood products or for fuel.

Survey.—Primary data for the LCI was collected through surveys in accordance with CORRIM and ISO 14041 protocols. Four (of seven requested) western mills and four (of nine requested) southern mills provided detailed responses for the material and energy inputs and outputs for each process unit in the sawmill complex for either calendar year 1999 or 2000.

Data quality.—The total production of the western mills was 1.91 million m^3 or 13% of the regional production and 9.1% of total western lumber production. The total production of the southern mills surveyed was 1.23 million m^3 or 6.3% of the regional production and 4.1% of all southern pine dimension lumber production. This is above the minimum required in the ISO protocol. Ten additional western mills provided detailed information for the energy generation and drying unit processes. The energy and drying data represent 20% of the western regional lumber production. These process units were more heavily surveyed because of the significant contribution they have on the environmental impacts. The sawmill complexes were of average technology for the regions, band saws in the West, and a mix of band saws, curved sawing and chip and saws in the South. An external critical review of the survey procedures, data, analysis, and report was done for compliance with CORRIM and ISO 14040 protocol.

Data analysis.—The survey results for each unit process were converted to a production basis (e.g., logs used per m^3 of lumber produced) and production-weighted averages were calculated for each material. Thus, we created a sawmill complex for each region that represents a composite of mills surveyed. The Franklin Database (Franklin Associates 2001) was used to assess off-site impacts associated with the materials and energy used. No environmental impacts were assigned to logs; however, other CORRIM projects are addressing this. SimaPro, version 5 (Pré Consultants 2001) was used as the accounting program to track all of the materials. All allocation was based on the mass of the products and co-products.

Most planed dry lumber reported in the surveys was 38 mm in thickness with widths from 63 to 286 mm. The weighted average width was 152 mm in the West and 172 mm in the South. The closest commercial width to the western average was 140 mm, and the majority of southern lumber was 38 to 184 mm in width. Therefore, the volume of planed, dry lumber produced was assumed to be all 38 by 140 mm for both LCIs, corresponding to U.S. nominal 2- × 6-inch lumber.

Data representativeness.—The primary data in the western survey indicated that 78.1% of the planed, dry lumber produced is western hemlock and 21.9% is Douglas-fir. For hemlock, 95% is sold dry compared to 18% for Douglas-fir. Comparing these results to secondary data published by the Western Wood Products Association (WWPA 2000) indicates that the survey data reflects relative amounts of products produced. The primary data in the southern survey indicated that planed dry southern pine accounts for nearly all dimension lumber production.

Western U.S. mills often produce both green and dry planed lumber and are not able to separate sawing and planing material inputs and outputs for green versus dry lumber production. However, the differences are minor and the annual data for these processes can represent dry lumber production. The major differences are that green lumber bypasses drying and the finished planed green sizes are slightly larger to account for future shrinkage.

Survey results

Logs, the main input, typically arrive at the mill by truck. The average haul distance is 113 km in the West and 92 km in the South.

Sawing.—Table 1 describes sawing processes which produce 1.914 m^3 of rough sawn green lumber in the West and 1.972 m^3 in the South. The actual sizes are 41.3 mm thick in the West and 43.1 mm in the South with a width of 150 mm. This is a larger size than the finished lumber to allow for shrinkage and planing. The volumes, 1.914 m^3 or 1.972 m^3, are equivalent to 1 mbf prior to drying and planing. Assuming no trim loss, this is the volume required to produce one functional unit of product. For the West, this is 78.1% hemlock and 21.9% Douglas-fir with a mass of 818 kg, which represents 56.8% of the mass of the products and co-products. For the South, this is southern pine with a mass of 883 kg, which represents 48.9% of the mass of the products and co-products. In the West, all of the hog fuel and bark and 7% of the sawdust are sent to the boiler. The chips and balance of the sawdust are sold off-site. In the South, approximately 70% of the sawdust and bark are sent to the boiler with the rest being sold off-site.

Western mills reported logs in units of Westside Scribner board feet. These were converted to a cubic measurement using values in Briggs (1994). The resulting log volumes sawn per unit of production calculated for each mill varied by 8% around the production-weighted mean, 3.05 m^3. We consider this to be good because of uncertainties due to the dependence on log diameter when converting the Scribner measure to an actual volume. As a second check, log mass into the process was within 8% of the sum of the co-products mass from the sawing unit process. We consider this to also be good agreement and note that mills have much better ability to accurately measure the products and co-products than the logs. Chip production varies among the western mills from 341 to 408 kg per 1.914 m^3 of rough green lumber, which again demonstrates consistency among the mills. The amounts of other co-products from sawing varied considerably; however, we attribute this to the way mills define the co-products. For example, bark or sawdust might be called hog fuel by some mills.

Three southern mills purchased logs based on mass and the other on U.S. South Scribner. The U.S. South Scribner value was converted to a mass using 7.25 tons/mbf. The mass for each mill was then converted to a volume using a wood specific gravity of 0.51 and a moisture content of 100%. The production-weighted average log volume was 3.92 m^3. The resulting log volumes sawn per unit of production calculated for each mill varied by 7.6% around the mean. As a second check, log mass in (dry measure) was within 4.5% of the sum of the co-products mass from the sawing unit process.

Water is mainly used in the process for wetting logs when they are stored prior to sawing. This varied from zero to 350 kg in the West and zero to 822 kg in the South. The high variability is because not all mills sprinkle logs.

Electricity is used to operate saws and conveyers, and the other fuels are used in log and lumber handling equipment, such as forklifts. Electrical use in western sawmills for the sawing process represents approximately 53% of that used by the mill complex. All purchased electricity in western mills is represented by production in Oregon and Washington in 2000 (74.3% hydro, 12.3% natural gas, 8.1% coal, 4.0% nuclear, and 2.3% other).

Electrical use in southern sawmills could not be divided among the unit processes based on the survey, which indicated that 150.9 kWh were used to produce 1.623 m^3 of planed dry lumber.

TABLE 1. *Process input and output table for sawing processes to produce 1.914 m^3 (1000 board feet at 1.65″ × 5.9″) of rough sawn western lumber or 1.972 m^3 (1000 board feet at 1.70″ × 5.9″) of rough sawn southern lumber. Co-products are dry mass and % is allocation.*

	West	South	Units
Resources			
Logs (PNW or SE)	3.05	3.92	m^3
Surface water	109	600	kg
Ground water	164.5	—	kg
Materials/fuels			
Organics (lubricants, etc)	0.34	1.06	L
Electricity (PNW or SE)	86.8	67.9	kW-hr
Propane	12.12	—	kJ
Gasoline equipment (BTU)	6.18	6.28	MJ
Diesel equipment (BTU)	65.8	57.3	MJ
Emissions to air			
Dust (coarse)	0.22	—	kg
Dust (PM10)	2.1	1.3	g
VOC	5.8	—	g
Acetaldehyde	<1	—	g
Acrolein	<1	—	g
Formaldehyde	<1	—	g
Methanol	2	—	g
Phenol	2	—	g
Solid emissions			
Wood	5	759	g
Bark	14	—	g
Inorganic general	1.79	1.12	kg
Other organic materials	0.16	—	kg
Coproducts			
Bark, green	111.8 (7.8%)	271.0 (13.2%)	kg
Hog fuel, green	18.3 (1.3%)	0 (0%)	kg
Sawdust, green	105.9 (7.3%)	123.1 (6.0%)	kg
Chips, green	384.1 (26.7%)	657.8 (31.9%)	kg
Lumber, rough green	818 (56.9%)	1007 (48.9%)	kg
Lumber, rough green (sold)	0 (0%)	1.6 (0.1%)	kg

We divided this among the process units based on the western survey, but placed slightly more in drying and energy generation because there is more water to be removed from southern pine. This is confirmed in Puettmann and Bowyer (2002) in which 28% of a southern mill's electrical use is at the kilns. This resulted in 45% to sawing, 25% to drying, 15% to the boiler, and 15% to planing. Purchased electricity in southern mills is represented by production in 2000 (1.8% hydro, 23% natural gas, 45.6% coal, 21.6% nuclear, 4.5% oil, and 3.5% other).

Surveys indicated that water-based products, such as paint and antistain treatments, account for less than 0.013% of the mass of the coproducts, including the water. Similarly, all other materials used in the sawing process were minor. None were highly toxic or resulted in hazardous waste.

Energy generation.—Steam in western mills was produced using three fuels: 58.2% from wood-based materials from the other processes, 41.7% from natural gas, and 0.1% from diesel. Steam in southern mills was all produced using wood-based materials. For natural gas and diesel, the Franklin databases for the effects of on-site combustion and off-site extraction, production, and transportation were used with a thermal efficiency of 80%. For wood-based fuels, the Franklin database was also used, but only for on-site combustion emissions because the fuel comes into the facility as logs.

One kg of dry wood material at 50% wet-basis moisture content (2 kg into boiler) contained 20.8 MJ of energy and produced 13.9 MJ of steam (67% thermal efficiency, Table 2). This is in good agreement with Wilén et al. (1996). In the West, a small amount of co-generated electricity was produced (2.3% of the electricity used in mill complex). In the West, the wood-based fuel was 80.1% bark, 13.4% hog fuel, and 5.6% sawdust. Because mills frequently had both wood- and gas-fired boilers, we could not determine electrical use by boiler type. In the South, the fuel mix was 60.7% sawdust and 39.3% bark. For each GJ of steam produced, 7.04 kWh of electricity was consumed in the West and 4.89 kWh in the South.

Drying (Table 3).—In western mills, the drying unit process converts 1.914 m^3 of rough green lumber to rough dry lumber. The mass of wood in and out is equal, 818 kg. For southern mills, these values are 1.972 m^3 and 1007 kg. The major non-lumber inputs to drying are steam and electricity. Electrical use in the dryer represents approximately 17% of that used by the mill complex in the West and an estimated 25% in the South. Steam comes from the three boiler types in the proportions described above in the West and from wood boilers in the South. Diesel in equipment is used for machinery, such as forklifts. Trailer diesel is used to transport lumber between the sawmill and kilns when the kilns are located at a different site (West only). The average haul distance to the dryers for the surveyed mills was 13 km. Some air emissions are attributed to drying, including VOCs that are emitted by the wood.

TABLE 2. *Process input and output table for energy generation process producing 1 GJ of steam from the combustion of wood-based fuel.*

	West	South	Units
Materials/fuels			
Hog fuel	9.7	—	kg
Bark	58.3	28.3	kg
Sawdust	4.1	43.6	kg
Electricity/heat			
Electricity (PNW or SE)	7.04	4.89	kWh
Emissions to air			
CO_2	151.0	151.0	kg
CO	0.98	0.98	kg
Acetaldehyde	0.0002	0.0002	kg
Formaldehyde	0.0033	0.0033	kg
Phenol	0.0028	0.0028	kg
NOx	0.11	0.11	kg
SOx	0.0054	0.0054	kg
Particulates	0.012	0.012	kg
Solid emissions			
Inorganic general	0.15	0.96	kg
Product steam	1 (100%)	1 (100%)	GJ

Planing.—In the West (Table 4), this unit process produced 1.623 m^3 of planed, dry lumber (1 mbf) from rough dry lumber. Electricity is used to operate the planer, saws, conveyers, and other equipment and the other fuels that are used in lumber handling equipment, such as forklifts. Plastic film, cardboard corners, and steel strapping are used to package the product for shipping. Surveys indicated that all other materials, such as paints for end-sealing, used in the process were minor. The co-products are sold offsite.

In the West, the planed dry lumber had a dry mass of 734 kg, which represents 86.1% of the co-product mass from this unit process. The mass of lumber from the survey in (852 kg) was very close to the sum of the mass of the co-products out (850 kg). Approximately 4% more lineal feet of lumber enters the planer than leaves due to end trimming to improve grade.

In the South, the planed dry lumber has a dry mass of 883 kg, which represents 85.0% of the coproduct mass from this unit process. The mass of lumber in from the survey (1007 kg) was very close to the sum of the mass of the products out (1038 kg).

Impacts for combined processes

The following discussion will be for all four unit processes—sawing, energy generation, drying, and planing—operating together to create 1.623 m^3 of planed dry lumber from logs. A mass balance on wood for the combined processes is shown in Table 5. The surveyed log input for western lumber is 1373 kg of wood. The surveyed wood products out are approximately 1402 kg, in good agreement surveyed input. The surveyed log input for southern lum-

TABLE 3. *Process input and output for drying 1.912 m^3 of rough sawn green lumber in the West and 1.972 m^3 in the South.*

	West	South	Units
Resources			
Surface water	3.64	—	kg
Materials/fuels			
Organics (lubricants, etc)	0.0006	—	L
Lumber, rough green	818	1007.5	kg
Electricity/heat			
Electricity, (PNW or SE)	27.8	37.7	kWh
Diesel equipment	9.4	8.0	MJ
Steam	3.30	3.85	GJ
Trailer diesel	39026	0	kg·km
Emissions to air			
Dust (coarse)	0.01	—	kg
VOC	0.09	1	kg
Solid emissions			
Inorganic general	0.01	—	kg
Non-wood organic materials	0.02	—	kg
Product (dry mass, % allocation)			
Lumber, rough dry	818 (100%)	1007 (100%)	kg

TABLE 4. *Process input and output table for planing process to produce 1.624 m^3 (1000 board feet at 1.5 in. × 5.5 in.) of planed dry lumber from rough dry lumber. For western lumber the rough dry input includes 4.14% additional length that will be trimmed.*

	West	South	Units
Resources			
Surface water	0.132	—	kg
Materials/fuels			
Lumber, rough dry	852	1007	kg
Organics (lubricants, etc)	0.048	—	L
LDPE film	5.9	—	g
Corrugated cardboard	1.7	—	g
Steel cold-rolled	0.147	—	kg
Electricity/heat			
Electricity, (PNW or SE)	27.2	22.6	kWh
Propane equipment	5.15		kJ
Diesel equipment	21.29	18.0	MJ
Emissions to air			
Dust (coarse)	37		g
VOC	16		g
Solid emissions			
Inorganic general	4		g
Non-wood organic materials	8		g
Coproducts (dry mass, % is allocation)			
Shavings (6.9%)	59.1 (6.9%)	155.5 (15.0%)	kg
Sawdust (1.3%)	11.3 (1.3%)	—	kg
Chips (5.4%)	46.4 (5.4%)	—	kg
Lumber, planed dry	734 (86.3%)	883 (85.0%)	kg

ber is 1999 kg of wood. The surveyed wood products out are approximately 1822 kg, again in good agreement surveyed with input.

It is important to note that when the western unit processes are linked, the unit processes for sawing and drying must operate 1.04 times for each one time the planing unit process operates due to the trim loss. This complicates the interpretation of the results. For southern lumber, no trim loss was reported and this complication

TABLE 5. *Mass balance on wood for the four unit process combined to manufacture 1.623 m^3 (1 mbf) of planed dry lumber from logs.*

	West		South	
Material	mass, kg	%	mass, kg	%
Planed dry lumber	774	50.3	883	42.2
Rough green lumber	0	0	1.6	0.1
Pulp chips	401	26.1	659	31.5
Sawdust (co product)	102.1	6.6	34.6	1.7
Sawdust to boiler	8.2	0.5	88.6	4.2
Planer shavings	59.2	3.8	155.5	7.4
Dry sawdust	11.4	0.7	0	0
Dry chips	46.5	3.0	0	0
Subtotal	1373	91.1	1822	87.0
Bark (co-product)	0	0	82.7	4.0
Bark to boiler	116.6	7.6	188.2	9.0
Hog fuel to boiler	19.1	1.2	0	0
Total	1538	100	2093.2	100

does not arise. Allocations are based on dry mass.

Raw materials.—The functional unit, 1.623 m^3 of planed dry lumber (1 mbf) is 53.2% of the log input for the West and 41.4% for the South. One would get these percentages by physically measuring lumber and log volumes. They are indicative of the greater volumes of chips and planer shavings produced in the South.

The allocation, however, can look quite different and Table 6 is included to help the reader understand how the allocation affects log use. In sawing, 59.7% and 48.7% of the log ends up as rough green lumber for the West and South, respectively. Rough green lumber has larger dimensions than planed dry lumber so the logs allocated to it are greater than the functional unit, 1.82 m^3 in the West and 1.91 m^3 in the South, reflecting a slightly larger target size in the South. The logs allocated to rough dry lumber increase because an additional portion of the log is consumed to produce the energy for drying. The increase is greater for southern lumber (48.7 to 62.5%) because all steam for drying was produced from wood-based fuel compared to the West (59.7 to 69.8%). The log volume allocated to planed dry lumber is lower than for rough dry lumber because a portion of the rough dry lumber is converted to shavings, chips, or sawdust at the planer. This is 13.6% in the West and 15.1% in the South.

TABLE 6. *Comparison of logs allocated to various processing stages in the West and South for the production of 1.624 m^3 (1000 board feet at 1.5 in. × 5.5 in.) of planed dry lumber. Percentages are based on log volume into mill.*

		Log (m^3) allocated to			
	Logs	Rough	Rough dry	Planed	Functional
West	3.05 m^3	1.82	2.13	1.84	1.62 m^3
	100%	59.7	69.8	60.2	53.2%
South	3.92 m^3	1.91	2.45	2.08	1.62 m^3
	100%	48.7	62.5	53.1	41.4%

Other raw material inputs would have a similar pattern if allocated to intermediate products, depending on where the raw material enters the process. Raw materials entering at the sawmill would follow the proportions shown in Table 4 for logs. A raw material or fuel, such as natural gas used for drying, would not appear for rough green lumber. It would be 100% allocated to rough dry lumber, and then allocated to planed dry lumber according to the proportions of products and co-products from the planer.

The raw materials needed to produce one 1.623 m^3 (1 mbf) of planed dry lumber are shown in Table 7. Logs were discussed above. Water is mainly for log decks. Natural gas use is mainly at the boiler in the West, but also for off-site electricity generation in both locations. Purchased electricity and natural gas extraction account for some of the other raw materials in

TABLE 7. *Raw materials used for the production of 1.624 m^3 (1 mbf) of planed dry lumber from logs. Substance not arising in cycle inventory are marked —.*

Substance	West	South	Unit
Logs, (PNW or SE)	1.84	2.08	m^3
Water, ground	97.9	317	kg
Water, surface	68.3	—	kg
Matural gas	42.4	7.32	kg
Coal	5.5	23.8	kg
Crude oil	3.3	3.54	kg
Iron	336.2	—	g
Limestone	151.4	1.37	g
Scrap, external	36.4	—	g
Wood/wood wastes	53.3	21.1	g
Natural gas (feedstock)	39.6	—	g
Wood for fiber (feedstock)	16.4	—	g
Crude oil (feedstock)	13.0	—	g
Oxygen	12.5	—	g

Table 1, especially in the West because of the natural gas use. Packaging materials (steel strapping, plastic lumber covers, and cardboard corners) were reported in the West and account for some of the materials that appear in the West but not the South.

Airborne emissions (Table 8).—Biomass CO_2 is CO_2 from non-fossil sources. This is further divided into on-site for the combustion of wood-based fuels at the boiler and offsite which occur in fuel or material preparation. Combined, 419 kg of CO_2 are emitted for each 1.623 m^3 of planed, dry western lumber produced and 574 for southern lumber. The overall CO_2 emissions are greater for southern lumber because more biomass fuel is used. The fossil CO_2 is higher in the West because of natural gas use at boiler. Fossil CO_2 emission also includes the fuels burned in machinery, such as forklifts, and off-site emissions associated with electrical generation and raw material production.

VOCs are due to organic compounds emitted on site, mainly from drying, and the other organic substances are off-site emissions. Most compounds are also generated off-site and are attributable to electricity and natural gas production, and the production of steel strapping, and plastic lumber covers. For the South, many of the other emissions are from electrical generation from coal compared to hydro in the West.

TABLE 8. *Airborne emissions for the production of 1.624 m^3 (1 mbf) of planed dry lumber from logs. Substances not generated by a process or its inputs are marked —.*

Substance	West	South	Unit
CO_2 (biomass—onsite)	260	493	kg
CO_2 (biomass—offsite)	42	5	g
CO_2 (fossil)	117	77	kg
CO_2 (total)	419	574	kg
CO	2.0	3.3	kg
SOx	1.6	0.7	kg
NOx	0.7	0.6	kg
Methane	305	159	g
VOC	129	848	g
Particulates	38	46	g
Particulates (unspecified)	16	61	g
Phenol	5.0	9.4	g
Particulates (PM10)	2.7	12	g
Formaldehyde	2.3	2.9	g
Methanol	0.9	—	g
Acetaldehyde	0.9	—	g
Acrolein	1	—	mg

Waterborne emissions (Table 9).—Waterborne emissions are all off-site. No mill in the survey discharged any process water. Most sawmills operate with this restriction. The water sprayed on logs is collected and recycled or soaks into the ground. Water used at the boiler and kilns is evaporated.

Solid emissions (Table 10).—These include ash generated at the boiler and the extraction of natural gas. Some waste collected from the logyard that is mixed with dirt and cannot be sent to the boiler is also included.

Energy use (Table 11).—The total energy (5462 MJ West, 6407 MJ South, HHV) allocated to the planed dry lumber includes purchased energy and embodied energy for the wood-based fuel consumed in the boilers. The South, with all of the steam for drying generated from wood-based fuels, has lower total for purchased energy than the West. The overall energy use is higher in the South, in part because more water is removed from each cubic meter of wood and because the conversion of the embodied energy in the wood-based fuel to steam for drying is less efficient than for natural gas.

The differences between the West and the South in the table reflect the sources for energy. Natural gas is by far the largest source of purchased energy for the manufacture of western lumber because 41.7% of the steam for drying is generated from natural gas compared with 0% in the south. Coal and uranium are higher for the South and hydro higher for the West because of the sources of energy for off-site electricity generation. Of the crude oil used in the West, 18% is attributable to natural gas extraction, 5% is

TABLE 9. *Cumulative waterborne emissions for the production of 1.624 m^3 (1 mbf) of planed dry lumber from logs.*

Substance	West	South	Unit
Dissolved solids	2.3	0.4	kg
Cl-	102.5	18	g
Suspended solids	48.5	44	g
Oil	39.6	6.9	g
COD	31.8	5.6	g
BOD	2.3	0.4	g

TABLE 10. *Solid emissions for the production of 1.624 m^3 (1 mbf) of planed dry lumber from logs.*

Substance	West	South	Unit
Solid waste	4.7	14.6	kg
Inorganic general	1.3	—	kg
Paper/board packaging	133.4	600	g
Wood	12.7	40	g

TABLE 11. *Energy use for the production of 1.624 m^3 (1 mbf) of planed dry lumber from logs. Values are higher values in MJ.*

Substance	West	South
Purchased		
Natural gas	2183	377
Energy from hydro	324	7
Coal	155	667
Crude oil	148	158
Uranium	64	276
Energy (undefined)	5	13
Subtotal for purchased	2879	1498
Wood and bark for fuel	2585	4909
Total	5462	6407

burned in the boiler, and the remaining 77% is used for diesel to power machinery such as skidders and forklifts. The coal in the West is 13% attributable to the production of steel to make the strapping, 66% to the extraction of natural gas, and the balance, 21%, to electrical generation. Similarly, uranium in the West is 78% attributed to natural gas extraction, 5% attributed to steel production, and the balance to electrical generation.

Table 11 does not reflect actual energy use at a mill, only the portions allocated to planed dry lumber following the LCI protocol. Actual purchased energy use is in Tables 1 to 4. If 100% of the energy were allocated to the planed dry lumber, 6412 MJ of purchased energy would be required for western lumber, for example. The relative amounts of energy used in different processes change due to allocation. For example, after allocation, 43.2% of the purchased electrical energy for producing western planed dry lumber is used in sawing, 19.8% in drying, 17.4% at the boiler, and 19.5% in planing compared to 66%, 19% to the dryer/boilers, and 15% to the planer for actual use based on the survey. The percent electrical energy used at the sawmill, for example, decreases compared to the survey because some is allocated to coproducts.

The effect of drying is significant. In the West, green lumber is a common product. If an LCI were done for the production of western planed green lumber, approximately 500 MJ of energy would have been required instead of 5462 MJ. Most of the reduction is due to not drying; however some of the difference is due to the energy allocation among coproducts.

Carbon balance

A mass balance on the carbon (Table 12) indicates that most of the carbon entering the process leaves with the products and co-products. Still, a significant amount is emitted to the atmosphere as biobased CO_2. Of that emitted to the air, 98% is CO_2 for western and southern lumber. The balance is CO and other organic compounds. CO_2 emissions are higher in the South because more wood fuel is burned to produce energy for drying.

CONCLUSIONS

The survey results were representative of the relative amounts of Douglas-fir and hemlock lumber produced in the western region. For both regions, the survey data represented the lumber sizes and production volumes, based on trade association production data. A good mass balance was obtained for each unit process. Logs, water, natural gas (West only), and diesel are the major raw materials used on-site. Many materials, such as paints, antistain chemicals, and

TABLE 12. *Carbon balance for wood-based carbon in for the manufacture of 1.623 m^3 (1 mbf) of planed dry lumber. Values are in kilograms.*

Substance	West	South
In		
Wood-based material	842.5	1054.9
Out		
Products and co-products	822.7	947.8
Air emissions out	85.2	165.1
Solid emissions out	0.0	0.4
Sum of C out	907.9	1113.3

packaging are used in small quantities, are ancillary, and comprise less than 0.1% of the product mass.

On-site emissions to land and water are small. On-site airborne emissions originate mainly at the boiler and are a function of the fuel burned. Electrical energy use is greatest in the sawmill; however, overall energy use and emissions are dominated by the drying process.

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