GATE-TO-GATE LIFE-CYCLE INVENTORY OF GLUED-LAMINATED TIMBERS PRODUCTION

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ABSTRACT

As part of the CORRIM Phase I research, this study completed a full gate-to-gate life-cycle inventory for the production of glued-laminated timbers (glulam) produced in two regions of the United States—the Pacific Northwest (PNW) and Southeast (SE). Data collected from surveys of manufacturers are presented for energy requirements, raw materials use, and emissions to land, water, and air allocated for one cubic meter and 1000 cubic feet of glulam. The glulam manufacturers surveyed represented 70 and 43% of the region's total glulam production for the PNW and SE, respectively. From both regions, 82% of the raw material and energy inputs and emission outputs were allocated to the glulam product, leaving the remaining 18% allocated to co-products. Contributions to the glulam process included impacts for the inputs of lumber and adhesives. Results show that wood drying and adhesive manufacturing make major environmental contributions to the glulam process. In addition, fuel sources, either biomass or fossil-based, have significantly different emission impacts to the environment. Wood fuel representing wood waste and hogged fuel accounted for nearly 50% of the cumulative energy consumed, while for wood fuel used for heat energy to dry lumber represented 65% and 100% for the PNW and SE glulam models. The cumulative energy from all fuel types including wood fuel allocated for one cubic meter of glulam was 6,748 MJ/m^3 when manufactured in the PNW and 7,213 MJ/m^3 when manufactured in the SE.

Keywords: Life-cycle inventory, LCI, glulam, carbon balance, building material, energy, emissions, glued-laminated timbers.

INTRODUCTION

The environmental attributes of a product or manufacturing process are becoming increasingly important and a regular part of choosing building materials. Wood is an environmentally versatile material. It is biodegradable, renewable, and recyclable. Unfortunately, the use of wood is increasingly under question, from local concerns of harvesting logs to global impacts of carbon emissions and global warming. The development of the life-cycle assessment (LCA) methodology has helped to quantify and provide information about a product where environmental qualities were lacking (Fava et al. 1991). A LCA is comprised of three interrelated components: 1) an inventory phase, 2) impact assessment phase, and 3) an improvement phase. The life-cycle inventory (LCI) conducted in this study is the quantitative result for softwood glued-laminated (glulam) timbers manufactured in the Pacific Northwest (PNW) and the Southeast (SE) United States. The LCI presented is focused on two main environmental assessments: 1) energy requirements, and 2) emissions to the environment for the production of glulam. The LCI developed in this study and all results are in accordance with the CORRIM Research Guidelines (CORRIM 2001) and the Interna-

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tional Organization for Standardization (ISO) protocol for performing life-cycle assessments (ISO 1997, 1998).

Background

Life-cycle inventory studies have been developed over the past two decades as a tool to evaluate the environmental impact of products or their processes. The Consortium for Research on Renewable Industrial Materials (CORRIM) recently completed LCIs on seven major wood building materials manufactured in the PNW and SE United States (Lippke et al. 2004). Prior to the CORRIM work, few have attempted to assess the environmental impact of an assortment of wood products (ATHENA 1993; Hershberger 1996; National Research Council 1976) with fewer yet to consider glulam timbers (Richter 1993). Richter's assessment of glulam timbers included information on energy and air emissions for harvesting, manufacturing, and transportation stages, but excluded type of energy and their subsequent air and water emissions and solid waste.

Structural glulam timbers are one of the oldest glued engineered wood products dating back to the late 1800s. Their uses are as concealed or exposed structural beams and columns in residential and commercial construction, warehouse roof beams and purlins, church arches, and girders and deck panels for timber bridges. Glulam timbers come in a variety of sizes with production based on volume basis, typically board feet (1 board foot = 0.0024 m^3), and sold by retailers on a linear basis (foot). Over one-half (60%) of glulam produced in the United States is used in domestic new residential and remodeling construction (Adair 2002). The next largest segment is the nonresidential market representing 31%. The remainder goes to industrial (4%) and export (5%).

Glulam has several advantages compared to solid-sawn timbers. Glulam has the advantage that the products can be made much larger than the trees from which the laminates (lumber) were sawn. Current log resources are comprised of much smaller diameters than were historically available, and sawmills are now adapted to accommodate smaller diameter logs. Glulam timbers can be designed to be several hundred feet long and up to 7 feet (2 meters) deep. One of the biggest advantages of glulam timbers is that they can be made with lower grade lumber incorporated with higher stressed grade lumber to allow for custom structural requirements where needed in the beam. In addition, glulam timbers can be designed to exhibit unique architectural effects. On the other hand, the manufacturing of glulam requires special equipment and adhesives that are not needed for the production of solid timber. These additional processes require additional energy and labor; therefore some of the advantages of glulam compared to solid-sawn timbers are reduced by certain factors that are not encountered in the production of solid-sawn timbers.

Scope of study

The scope of this study details glulam timber production practices from two major wood product-producing regions in the United States, the PNW representing Oregon and Washington, and the SE representing Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, and Texas. Total annual glulam production in 2000 from these regions was 261,931 m^3 (111 million board feet, nominal) and 327,872 m^3 (139 million board feet, nominal) for the PNW and SE regions, respectively (APA 2001). The production totals represent 31% and 39% of the total U.S. glulam production for the PNW and SE, respectively.

This report documents the life-cycle inventory (LCI) of glulam beam manufacture based on softwood resources from the two regions. While primary data were collected through surveys, secondary data were obtained from available databases (EIA 2001; FAL 2001; Milota 2004, Milota et al. 2004; Nilsson 2001).

Product process and description

A single-unit process approach was taken in modeling the LCI of the glulam process although several individual steps are part of glulam manufacturing. A typical manufacturing process consists of lumber drying (when purchasing green lumber), trimming, finger-jointing or end-jointing, planing, face bonding, planing, and finishing and fabrication (Fig. 1). Before shipping, each beam is typically individually wrapped for protection from weather. To minimize dimensional changes, the lumber must be kiln-dried to a maximum moisture content of 16% (AITC 1983). Lumber used may be purchased green and dried in on-site lumber kilns or purchased pre-dried from lumber suppliers. Lumber with moisture contents greater than the threshold are removed from the process and re-dried. Re-drying is accomplished through either air or kiln-drying depending on the amount of water that must be removed.

To manufacture glulam timbers in lengths beyond those commonly available for lumber, laminations must be made by end-jointing to the proper length. The most common end-joint is a finger-joint. Joints are cut on both ends of the lumber. A structural resin, such as melamine-urea-formaldehyde (MUF), is applied and cured under pressure and heat. Most manufacturers use a continuous radio-frequency (RF) curing system for this step. The laminations are planed and adhesive is applied with a glue extruder. Phenol-resorcinol-formaldehyde (PRF) is the most commonly used resin for face bonding. The laminations are then assembled into the required lay-up and pressure is applied. Two types of curing methods used are cold cure (CC) (that uses only pressure and ambient heat for curing) and radio-frequency cure (that uses pressure and heat in excess of 93°C). After proper pressing and curing time, the glulam timbers are removed from the presses and then the wide faces are planed to remove adhesive that has squeezed out during pressing. The remaining two faces of the member may be lightly planed or sanded. For premium and architectural classifications, knots and planer skips are patched. Depending upon use, final cuts are made, holes are drilled, connectors are added, and a finish may be applied. Each timber is individually wrapped for protection during delivery.

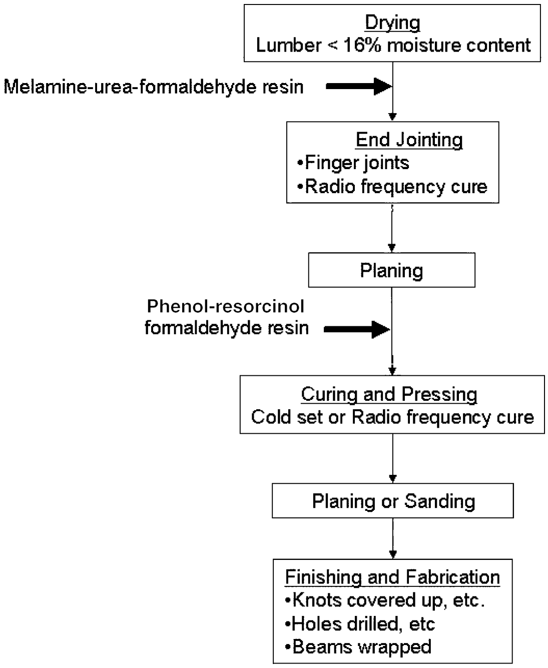

FIG. 1. A single-unit process approach used to model the glulam manufacturing process.

Functional unit

The functional unit, the unit that all inputs and outputs are allocated to, is one cubic meter (m^3) or 1000 cubic feet (MCF), actual volume of glulam timbers, which includes lumber and resin. One thousand cubic feet (MCF) is equal to 19.02 thousand board feet (MBF) of nominal volume. The system boundary is a gate-to-gate, covering the production of lumber and resins to the production of the product (glulam) and co-products (shavings and trimmings). A co-product is defined as a material, other than the principal product, that is generated, and leaves the system boundary, usually because it has some economical value or function. All input and output data for the production of glulam timbers were allocated based on the mass of products and co-products produced in accordance with ISO allocation procedures (ISO 1997, 1998).

System boundaries

The general system boundary encompasses glulam timber production and the materials needed for glulam manufacturing (i.e. lumber and resin), excluding raw material transport to the production facility (Fig. 2). Transportation distances are reported, but burdens associated with transportation are omitted from this study. The cumulative system boundary (solid box) includes the production of softwood lumber (Milota 2004; Milota et al. 2004) and resin materials (Nilsson 2001), production of electricity, natural gas, diesel, gasoline, ancillary materials, and glulam timbers and its co-products (Fig. 2), excluding log resources. The on-site system boundary for the on-site glulam LCI model (dotted line box) includes those processes that take place at the glulam facility (Fig. 2). Burdens associated with resource extraction, lumber production, fuel and electricity production, resin production, and all production and transportation of raw materials and fuels have been omitted from the on-site analysis. Included in the on-site system is the combustion of fuels used on-site and emissions generated from glulam production and curing the beam.

A full cradle-to-gate life-cycle inventory of wood products from CORRIM phase I reports that include harvesting and transportation are presented in this issue (Puettmann and Wilson 2005).

Data collection, quality, and assumptions

Procedures for data collection and analysis, and formulation of assumptions followed guidelines defined by CORRIM and the International Organization for Standardization procedures on life-cycle inventories (CORRIM 2001; ISO 1997, 1998). Primary data were collected by survey of glulam manufacturers in each region for the 2000 production year while data in the form of fuel used and emissions to produce energy and electricity and resin production were obtained from available databases (ATHENA 1993; EIA 2001; EPA 2003; FAL 2001; Nilsson 2001; PRé Consultants 2001). To conduct the survey, glulam plants were preliminarily screened and identified based on their production capability and representation of the industry. Manufacturing plants provided data in terms of energy, raw material, and ancillary inputs; products and co-product production; and emissions to air, water, and land. Detailed description of the surveys can be found in the final reports (Puettmann and Wilson 2004).

In the PNW, the glulam producers surveyed represented 70% of the region's production of 183,959 m^3 (78 million board feet, nominal)

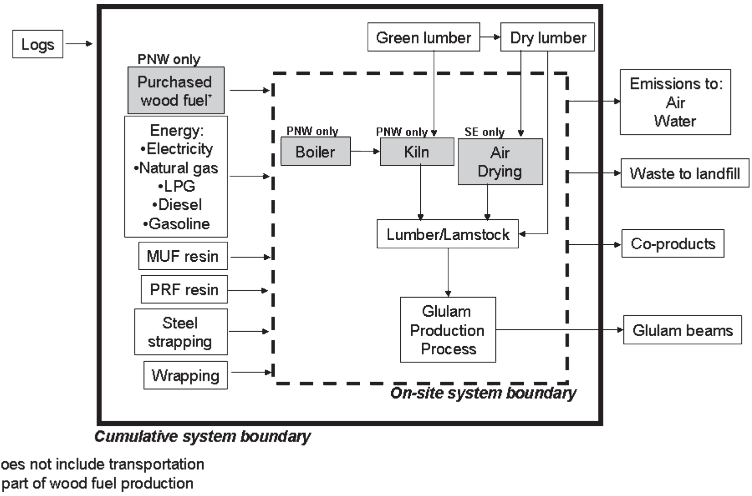

FIG. 2. Cumulative (solid line) and on-site (dotted line) system boundaries for glulam production used to model the PNW and SE manufacturing process. Burdens associated with electricity and fuel production, resin and lumber production, raw material production, and transportation are not included within the on-site system boundary. Forest growth, management, and harvesting, wood fuel production, and transportation are not included in the cumulative system boundary.

(APA 2001). For the SE region the glulam producers surveyed represent 43% of the region's production having a total annual production at 141,528 m^3 (60 million board feet, nominal).

All data from the survey were weighted-averaged based on a particular plant's production in comparison to the total survey production for the year. Missing data were defined as data not reported in surveys by the glulam producers. Missing data were carefully noted so they were not averaged as zeros. When data were missing for an input category, the weighted-average for that category reflected those facilities reporting the data in the surveys.

Glulam timbers are made of various species in the PNW region with Douglas-fir (*Pseudotsuga menziesii,* (Mirbel) Franco) dominating, but western larch (*Larix occidentalis,* Nutt.) and Alaskan yellow cedar (*Chamaecyparis nootkatensis,* (D. Don) Spach) are commonly used. In the SE United States, glulam timbers are made primarily from southern pine species (*Pinus Palustris* Mill., *P. echinata* Mill, *P. taeda* L., *P. elliottii* Engelm.). A single wood density value for each region was derived using published values and based on their weighted percentage of each species as reported by manufacturers (FPL 1999). The PNW weighted-average wood density was calculated to be 474 kg/m^3 (29.6 lb/ft^3). The weighted-average density for SE glulam was calculated to be 556 kg/m^3 (34.7 lb/ft^3). Lumber inputs were provided in board feet (BF) (Milota 2004; Milota et al. 2004) and converted to actual volume using derived conversion factors by Puettmann and Wilson (2004). The mass of the input lumber was determined by converting nominal board feet to actual volume (cubic meters or cubic feet). An actual to nominal ratio was derived based on average percentages of each size beam produced (Puettmann and Wilson 2004). Final conversions were calculated from volume to mass by multiplying by the weighted-average densities as determined by the species representation reported in the surveys.

All lumber was considered purchased as lamstock. Lamstock is defined as a special grade of lumber used in constructing laminated timbers. The lamstock lumber produced in the PNW was assumed to be cut to 50.8 mm × 101.6 mm (25%), 50.8 mm × 154.4 mm (55%), 50.8 mm × 203.2 mm (15%), and 50.8 mm × 254 mm (5%) (all actual dimensions). For the SE 65% of the lamstock was cut to 50.8 mm × 154.4 mm and 35% cut to 50.8 mm × 203.2 mm. The mass difference between reported input and output wood material flows was 9.3% for the PNW and <1% for SE. This difference is referred to herein as "unaccounted wood" (Table 1). In the input process model in SimaPro, the "unaccounted wood" mass was added to the purchased kiln-dried lumber coming from the softwood lumber models (Milota 2004; Milota et al. 2004). It is assumed that the "unaccounted wood" may have come from lumber that was purchased the previous year and not included in the inventory for 2000.

All conversion units for logs and forest products followed published factors specific for the industry in each region (Briggs 1994). An international life-cycle assessment (LCA) software package (SimaPro5) designed for analyzing the environmental impact of products was used to develop the glulam life-cycle inventory (LCI) tables (PRé Consultants 2001). This LCA software also contains a U.S. database for a number of materials, including paper products, fuels, and chemicals (FAL 2001).

Product yields

The percentage of recovery of wood in terms of wood input as lumber and output as glulam timbers was 82% for the both PNW and SE LCI models. This allocation was derived using the weight of wood in glulam timbers divided by the total weight of wood input times 100. For the functional unit of one cubic meter or 1000 cubic feet (in parentheses), the mass allocated to glulam timbers yielded 483 kg (30,162 lb), and 551 kg (34,400 lb) for the PNW and SE respectively. A complete wood mass balance is given in Table 1.

Transportation

Burdens associated with transportation were not part of the system boundaries (Fig. 2). Sur-

TABLE 1. *Wood mass balance (wighted averages) for glulam production per cubic meter (m^3) or 1,000 cubic feet (MCF) based on actual volume.*

	Pacific Northwest		Southeast	
	kg/m^3 (lb/MCF)	% allocation	kg/m^3 (lb/MCF)	% allocation
Inputs				
Lumber	537 (33,498)		670 (41,800)	
Unaccounted wood[1]	55 (3,424)		6 (362)	
Total	592 (36,922)		676 (42,162)	
Outputs				
Glulam beams (wood only)	483 (30,162)	82	551 (34,400)	82
Shavings and trimmings	89 (5,535)	15	119 (7,140)	17
Wood waste	20 (1,233)	3	6 (381)	1
Total	592 (36,929)	100	676 (42,191)	100

[1] Unaccounted wood input is assumed to be lumber already on-site prior to year of survery.

vey mills provided delivery distances and are considered part of the system boundary in a cradle-to-gate analysis for wood products (Puettmann and Wilson 2005). The delivery of raw materials to the glulam facilities was made by truck. For informational purposes only, the one-way delivery distance for raw materials (lumber, resin, strapping, and wrapping paper) to glulam facilities is given in Table 2.

SimaPro model structure

Survey data representing the single unit process as defined in Fig. 1 for glulam production were entered into the LCA software (Tables 3 and 4). Data input was primary data from the surveys, but environmental data associated with the data were obtained from the Franklin database. For example, the quantity of diesel fuel was reported in the surveys, but the environmental data associated with the manufacturing, transportation, and combustion of diesel fuel were obtained from the other sources. In addition, a four-unit process for the production of PNW lumber and SE lumber (Milota 2004; Milota et al. 2004) and a single-unit process for producing phenol-resorcinol-formaldehyde (PRF) or melamine-urea-formaldehyde (MUF) resins were imported and used in the glulam LCI model. Tables 3 and 4 show the inputs as they were entered into the LCA software. Input emissions shown in these tables are for the glulam on-site production process and are considered primary data, that is, they were obtained from the glulam surveys. Emissions listed in Tables 3 and 4 are associated with glulam on-site production only, excluding emissions resulting from the manufacturing, transportation, and combustion of fuels. All values in Tables 3 and 4 are not allocated and reflect actual energy consumed and emissions released at the glulam facilities to manufacture glulam and all co-products that might be produced.

TABLE 2. *Weighted average delivery distance (one-way) used for glulam production as reported in glulam surveys. Burdens associated with transportation of the materials are not included in the SimaPro glulam LCI model.*

	One-way delivery distance	
Material	PNW kilometers	SE kilometers
Lumber, green	52	N/A
Lumber, dry	139	433
Resin (PRF and MUF)	70	689
Steel strapping	811	1,219
Wrapping material	172	1,843

Note: Lumber production deliverables not included; for these values, see Milota (2004) and Milota et al. (2004).

LIFE-CYCLE INVENTORY RESULTS

Sources of energy

Energy for the production of glulam timbers comes from electricity, natural gas, purchased wood fuel (hogged fuel or biomass fuel), gasoline, diesel, and liquid petroleum gas (LPG) (Table 5). A small amount of kerosene was reported for use in space heaters. The electricity is used to operate RF presses, pneumatic and mechanical conveying equipment, fans, hydraulic

TABLE 3. *Total process inputs as entered into the SimaPro model for the production of Pacific Northwest glulam. All input data are per cubic meter glulam (m^3) of glulam and were collected from surveys. Data are a weighted average based on the 2000 production year. Co-products included. (Not allocated)*

	Unit	Unit/m^3		Unit	Unit/m^3
Materials/fuels			Emissions to air		
Steel for strapping	kg	0.28	VOC	kg	0.2883
Liquid petroleum gas (LPG)	MJ	41	Methanol	kg	0.0104
Kerosene	MJ	0.001	Phenol	kg	0.0105
Gasoline	L	0.09	Formaldehyde	kg	0.0003
Diesel	L	0.36	Particulates	kg	0.5671
Lumber, green	kg	149	Isopropanol	kg	0.2098
Lumber, dry	kg	442	Ethanol	kg	0.0050
LDPE film recycled—wrapping	kg	1.42	Resorcinol	kg	0.0000
Kraft unbleached—wrapping	kg	1.54	Particulates (PM10)	kg	0.0513
Melamine-urea-formaldehyde (MUF)	kg	0.96			
Phenol-resorcinol-formaldehyde (PRF)	kg	5.17	Resources		
Hardener, MUF	kg	0.11	Water (process)	kg	35,721
Hardener, PRF	kg	0.95			
			Products		
Electricity/heat			Glulam beams, PNW	kg	484
Natural gas—Process heat	MJ	153			
Electricity	MJ	304	Co-products		
Wood fuel energy—for lumber drying in glulam process	MJ	129	Shavings, PNW	kg	87
			Trimmings, PNW	kg	1.40
Wood fuel energy—glulam process heat	MJ	379	Landscaping, PNW	kg	20

TABLE 4. *Total process inputs as entered into the SimaPro model for the production of Southeast glulam. All input data are per cubic meter glulam (m^3) of glulam and were collected from surveys. Data are a weighted average based on the 2000 production year. Co-products included. (Not allocated)*

	Unit	Unit/m^3		Unit	Unit/m^3
Materials/fuels			Emissions to air		
Steel for strapping	kg	0.38	VOC	kg	0.8298
Natural gas	MJ	11	Particulates	kg	0.8970
Gasoline	L	0.39	Particulates (PM10)	kg	0.8970
Kraft unbleached—wrapping	kg	2.23	HAPS, total	kg	0.4197
Diesel	L	0.66			
LDPE film recycled—wrapping	kg	2.05	Solid emissions		
Phenol-resorcinol-formaldehyde	kg	7.96	Particulates from pollution abatement equip.	kg	1.67
Melamine-urea-formaldehyde	kg	0.77			
Hardener, PRF	kg	1.10	Resource		
Hardener, MUF	kg	0.07	Water (process)	kg	1,405
Lumber, dry	kg	567			
Lumber, green	kg	102	Products		
			Glulam beams, SE	kg	551
Electricity/heat			Co-products		
Natural gas—Process heat	MJ	1,013	Shavings, SE	kg	64
Electricity	MJ	356	Trimmings, SE	kg	55
			Wood waste, SE	kg	5.33

pumps, and saws. Wood fuel was used in a boiler for heat input for a green lumber dry kiln (one mill only) and for process heating in the PNW. Natural gas was also used for process heating in other glulam facilities both in the PNW and SE producing regions. On-site trucks and forklifts used diesel, gasoline, and LPG. Based on the glulam surveys in the SE, wood

TABLE 5. *On-site glulam process fuel inputs (gate-to-gate) reported in surveys allocated to one cubic meter (m^3) of glulam timbers from the Pacific Northwest (PNW) region and Southeast (SE). Energy content based on higher heating values (HHV). (Allocated)*

		PNW		SE	
	Unit[1]	Unit/m^3	MJ/m^3	Unit/m^3	MJ/m^3
Wood fuel	kg	20	417	0	0
Natural gas	m^3	3	126	22	827
Liquid petroleum gas	L	1	35	0.3	9
Diesel fuel	L	0.3	12	0.5	21
Gasoline	L	0.1	0.3	0.3	1
Electricity	MJ	248	248	292	292
Total			929		1,153

[1] As reported in surveys

fuel was not used in any of the manufacturing processes. All wood fuel use shown for SE glulam manufacturing is a result from producing lumber from the SE (Milota et al. 2004).

Cumulative energy is defined as the total fuel energy (production and combustion) allocated for the manufacture of one cubic meter or 1000 cubic feet of glulam timbers. This includes the cradle-to-gate burdens associated with the production of all fuels (coal, crude oil, natural gas, wood, and uranium) used in glulam processing, resin production, lumber production, and electricity generation. Figure 2 shows the cumulative system boundary and the energy and resource requirements that are included in that boundary. Energy for harvesting operations to bring logs into the system are not included in this analysis, as well as transportation needed to bring resources (excluding fuels) into and between system boundaries.

On-site energy is that energy allocated to one cubic meter or 1000 cubic feet of glulam timbers and combusted on-site for the glulam production process. This would be energy in the form of natural gas, diesel, gasoline, wood fuel, LPG, and electricity. Energy required to produce these fuels and deliver them to the glulam production site are excluded from this system boundary.

Electricity use summary

The source of fuel used to generate electricity has a major impact on the types of emissions resulting from energy production. Sources of fuels used in electricity generation were provided by the Department of Energy (EIA 2001). In 2000, the dominant source of electricity in the PNW region was hydro, representing 74.3% of the total, followed by natural gas at 12.3% and coal sources at 8.1%, while for the SE glulam region the dominant fuel source was coal (45.6%) with natural gas and nuclear contributing 23 and 22%, respectively. Within the Franklin database (FAL 2001), no impacts are associated with hydro-generated electricity in the United States; however, combustion of coal can result in significant impacts. Considering the cumulative glulam production process allocated to one cubic meter of glulam, the manufacturing of glulam timbers required 52% of total electricity consumed, with lumber and resin production requiring 42 and 6%, respectively. When comparing total energy for electric power differences between cumulative (lumber, resin, and glulam production) and on-site (glulam production) models, the burdens associated with lumber and resin production increased energy demand for electricity by 116% in the PNW and 92% in the SE region. These larger increases show the energy intensiveness of lumber drying and resin production and emphasized the need to consider fuel type for energy generation.

Process energy for electric power required for glulam production for both cumulative (includes lumber and resin production) and on-site (gate-to-gate) models was 525 and 249 MJ/m^3 of glulam in the PNW region and 556 and 290 MJ/m^3 for cumulative and on-site (gate-to-gate) in the SE region

Thermal energy requirements

Only one boiler was reported in the glulam surveys that used wood fuel as its fuel source. The boiler was used to provide heat to a kiln to dry lumber purchased at greater than 16% moisture content, and for process heat. From surveys, wood fuel weights, following industry practice, were given as green weight and assumed to be 50% moisture content on a wet-weight basis. As such, the cumulative wood fuel burned for use in boilers is 141 kg/m^3 and 113 kg/m^3 (oven-dry basis) for the PNW and SE, respectively (includes wood fuel for lumber production). In the PNW region, lumber production accounted for 67% of the wood fuel energy consumption or 2,946 MJ/m^3. No boilers were reported in the SE glulam production surveys. Boilers were reported for wood drying energy requirements in the SE lumber model (Milota et al. 2004), providing energy of 2,367 MJ/m^3. In addition to wood fuel, diesel and natural gas were also used in boilers for kiln-drying lumber produced in the PNW region. The boiler allocation was 58.2% wood fuel, 41.7% natural gas, and 0.1% for diesel (Milota 2004). These fuel requirements were allocated to glulam production in the PNW region. A slight amount (<1%) of diesel fuel was also used in the SE lumber production and allocated to the SE glulam production for lamstock.

Emissions associated with combustion of boilers were obtained from the U.S. database (FAL 2001) within the LCA software SimaPro and from a government database (EPA 2003). The emissions resulting from burning wood fuel and fuel consumed in generating wood fuel are included in the LCI tables. Resource extraction and transportation of the wood fuel are not included in these data. Possible future work involves developing processes for wood combustion boilers to include cradle-to-gate life-cycle inventories, taking into account wood products industry type, geographic location, wood species, transportation, and fuel source, i.e. bark, or wood. To date, CORRIM has collected boiler data from manufacturers of softwood plywood, glulam, laminated veneer lumber, softwood lumber, and oriented strandboard (OSB) (Kline 2004; Milota 2004; Milota et al. 2004; Puettmann and Wilson 2004; Wilson and Dancer 2004; Wilson and Sakimoto 2004).

Cumulative energy requirements

The gate-to-gate cumulative energy for the production of glulam timbers includes lumber and resin production. Energy associated with harvesting logs and transportation of raw materials is omitted. Energy values have been determined by using the higher heating values (HHV) given in Table 6. Energy from natural gas and wood fuel burned has the largest contribution to total energy (Table 7). In the PNW model, natural gas and wood fuel make up 39 and 47% of the total, while in the SE, wood fuel burned is over 52% and natural gas at 27% of total energy. Crude oil and coal also contribute to fuel consumption in the SE model, representing 6 and 12%, respectively. While electricity generation from hydro-power made up approximately 75% in the PNW model, when analyzing total fuel consumed (diesel, gasoline, natural gas, electricity, LPG, and wood fuel) from all fuel sources (coal, crude oil, natural gas, hydro, uranium, and biomass), hydro contributed less than 6% of the energy. This is less than that of crude oil in the SE model.

Emissions to air, land, and water

Sources for air emission come from fuel production, fuel use, resin manufacturing, and process emissions for the production of lumber and glued-laminated timber as reported in surveys. Cumulative emissions reported for one cubic meter (m^3) and 1000 cubic feet (MCF) of glulam timbers are reported in Table 8 for emissions to air and water and Table 9 for emissions to land. Biomass carbon dioxide (CO_2 (biomass)) is CO_2 emitted by the combustion of non-fossil-based fuels. In the glulam models reported here, the source of biomass comes primarily from wood and wood/waste fuel. The total CO_2 emitted as a result of biomass combustion was 230 kg/m^3

TABLE 6. *Heat values used to convert raw materials for fuel production into energy values.*

Fuel type	Higher heating value (HHV) (MJ/kg)
Natural gas	54.4
Wood fuel/wood waste (oven-dry)	20.9
Crude oil	45.5
Coal	26.2
Uranium[1]	381,000
Gasoline	48.4
Diesel	44.0

[1] Expected heat value for U.S. nuclear industry generation of electricity.

TABLE 7. *Cumulative energy requirements allocated to one cubic meter of glulam timbers produced in the Pacific Northwest (PNW) and Southeast (SE) United States. Includes fuel used for lumber and resin production and electricity. (Allocated)*

	Cumulative energy			
	PNW	SE	PNW	SE
	kg/m^3		MJ/m^3	
Natural gas	49	36.27	2,663	1,978
Wood fuel/ wood waste	153	182	3,198	3,804
Hydro-power	—	—	376	21
Crude oil	6	9	268	420
Coal	8	34	207	893
Uranium	0.0001	0.0002	30	85
Other energy	—	—	6	12
Total			6,748	7,213

compared to 106 kg/m^3 of CO_2 fossil in the PNW model. This indicates the strong use of bio-based fuel source for glulam production. Nearly 67% of the biomass CO_2 comes from the production of lumber used in the glulam manufacturing process. Similarly in the SE glulam model, 231 kg of CO_2 biomass are emitted. In this model, nearly all the wood fuel combustion comes from the lumber production model (Milota et al. 2004). The overall CO_2 fossil emission is greater for the SE glulam process. The glulam manufacturers from this region reported no biomass use and all used natural gas fuel source for process energy.

Other air emissions reported come from the resin and fuel production processes, including electricity generation. VOCs are due to organic compounds emitted mainly from combustion of wood fuels. Of the cumulative VOCs reported in Table 9, 76% are from on-site wood combustion (Table 10).

The reported emissions to water, all originate from fuel, resin, and lumber production (Table 8). Surveyed glulam manufacturers from both regions did not report any emissions to water. Most of the emissions (solid waste) to land also originated from the production of fuels and resin. The slag and ash generated at the boiler in the lumber models were reported in the surveys (Table 9). Glulam manufacturers reported solid waste and waste collected in pollution abatement devices (reported here as solid waste) (Table 10). Of the cumulative solid waste reported, 5% originated on-site from the PNW model and less than 1% from the SE glulam model (Tables 9 and 10).

On-site emissions are those emissions reported in manufacturer surveys for the production process of glulam timbers. Also included in on-site emissions, but not reported in the surveys, are combustion emissions from fuel used on-site. In the case of glulam manufacturing, fuels reported in surveys were diesel, gasoline, kerosene, LPG, natural gas, and wood fuel (Table 5). Table 10 contains the total on-site emissions for the combustion of these fuels and process emissions reported by manufacturers. The major difference between the PNW and SE glulam models is that in CO_2 fossil and CO_2 biomass. Manufacturers from the PNW region used wood fuel as the major fuel source for wood drying and process energy, while in the SE region, glulam manufacturers did not need to dry lumber; therefore, they used only natural gas for process energy, hence resulting in no CO_2 biomass. Other differences are mainly due to how the glulam manufacturers reported their emissions in the surveys. The PNW manufacturers reported HAPS (Hazardous Air Pollutants) as individual substances (e.g. methanol, phenol), while the SE manufacturers reported these as total HAPS. No on-site water emissions were reported in the surveys or in the database for combustion of fuels used on-site (FAL 2001).

Adhesive use

Phenol-resorcinol-formaldehyde (PRF) and melamine-urea-formaldehyde (MUF) are the adhesives used in glulam production. The MUF resin is used in the finger-jointing of the laminates to the make the desired length of the finished timber, and the PRF resin is used in face bonding the laminates for the finished depth (thickness) of the beam. The manufacture of these resins is energy-intensive. The PRF resin was composed of 85% resin and 15% hardener, while MUF was composed of 90% resin and 10% hardener. The production of one cubic me-

TABLE 8. *Cumulative emissions to air and water allocated to one cubic meter (m^3) or 1000 cubic feet (MCF) of glulam timbers produced in the Pacific Northwest (PNW) and Southeast (SE). Results include the production of lumber, electricity, fuels, resins, and ancillary materials. Transportation of resource to the sawmill and transportation of raw materials to the glulam facility have been omitted. (Allocated)*

	PNW		SE	
	kg/m^3	lb/MCF	kg/m^3	lb/MCF
Emissions to air				
Acetaldehyde	0.0007	0.0413	0.0003	0.0206
Acrolein	0.0000	0.0000	0.0000	0.0001
CO	1.7900	112	1.9200	120
CO_2 (biomass)	230	14,374	231	14,453
CO_2 (fossil)	106	6,590	164	10,200
Formaldehyde	0.0022	0.1350	0.0021	0.1330
HAPS, total	—	—	0.3440	22
Methane	0.2720	17	0.3860	24
Methanol	0.0100	0.6240	0.0010	0.0631
N_2O	0.0003	0.0188	0.0009	0.0534
NMVOC	0.3330	21	0.3300	21
NOx	0.6000	41	0.8690	54
Particulates	0.4950	31	0.7640	48
Particulates (PM10)	0.0455	3	0.7550	47
Particulates (unspecified)	0.0405	3	0.0834	5
Phenol	0.0131	0.8190	0.0045	0.2830
SO_2	0.0212	1.3300	0.0304	1.9000
SOx	1.2900	81	1.6300	102
VOC	0.3080	19	1.1400	71
Total	341	21,295	403	25,170
Emissions to water				
BOD	0.0036	0.2250	0.0044	0.2740
Cl^-	0.0782	5	0.0753	5
COD	0.0469	3	0.0563	4
Dissolved solids	1.7300	108	1.6800	105
Oil	0.0301	2	0.0291	2
Suspended solids	0.0590	4	0.1050	7
Total	2	122	2	123

ter of glulam required 5 kg of PRF and 1 kg of MUF resin, and the energy to produce and transport these resins was 613 and 40 MJ/m^3, respectively for the PNW, accounting for about 10% of the cumulative energy (Table 7). Similarly in the SE, the resin requirements were 7 kg of PRF and 1 kg of MUF, requiring manufacturing energy of 624 and 31 MJ/m^3, respectively, or about 9% of the cumulative energy allocated to one cubic meter of glulam. Emissions from production and energy use for resin production are incorporated within the cumulative LCI tables (Tables 8 and 9). Complete life-cycle inventory tables for resins (Nilsson 2001) used in the glulam production for the two production regions can be found in

TABLE 9. *Cumulative solid waste allocated to one cubic meter (m^3) or 1000 cubic feet (MCF) of glulam timbers produced in the Pacific Northwest (PNW) and Southeast (SE). Results include the production of lumber, electricity, fuels, resins, and ancillary materials. Transportation of resource to the sawmill and transportation of raw materials to the glulam facility have been omitted. (Allocated)*

	PNW		SE	
Solid waste	kg/m^3	lb/MCF	kg/m^3	lb/MCF
Slags/ash	0.0124	0.7750	0.0174	1.0900
Inorganic general	0.6850	43	—	—
Wood	0.0070	0.4340	0.2360	15
Solid waste	17	1070	20	1230
Other	0.0484	3.644	0.0838	5.235
Total	18	1,118	20	1,250

TABLE 10. *On-site air emissions and solid waste allocated to one cubic meter (m^3) or 1000 cubic feet (MCF) of glulam timbers produced in the Pacific Northwest (PNW) and Southeast (SE). Results include only those burdens associated with glulam production at the facility. Results do include emissions associated with wood combustion from on-site wood boilers and the combustion of fuel used on-site (diesel, gasoline, kerosene, LPG, natural gas). Transportation of raw materials to the glulam facility is omitted. (Allocated)*

	PNW		SE	
Emissions to air	kg/m^3	lb/MCF	kg/m^3	lb/MCF
Acetaldehyde	0.0001	0.0068	—	—
CO	0.5473	34	0.1720	11
CO_2 (biomass)	76	4,730	—	—
CO_2 (fossil)	8	476	9	589
Formaldehyde	0.0008	0.0503	0.0006	0.0388
HAPS, total	—	—	0.3440	22
Methanol	0.0085	0.5300	—	—
NMVOC	0.0399	3	0.0491	3
NOx	0.1840	11	0.1460	9
Particulates	0.4716	29	0.7378	46
Particulates (PM10)	0.0419	3	0.7350	46
Phenol	0.0100	0.6250	—	—
SOx	0.0044	0.2721	0.0023	0.1420
VOC	0.2350	15	0.6810	43
Total	86	5,302	12	769
Solid waste total	3	206	1	85

the glulam final report (Puettmann and Wilson 2004).

From the PNW manufacturers surveyed, glulam produced by the cold cure (CC) pressing process represented only 15% of the total production but used 65% more PRF and nearly 60% more MUF. In the SE the glulam timbers produced by the CC process (54%) represented more of the total production than radio-frequency (RF) processing. Similar to the PNW resin consumption, CC processing in the SE used nearly 70% more MUF and PRF resin than the RF processing. This increased use of resin is most likely due to the nature of lay-up process where the energy used in the RF pressing allows for less resin applied.

Carbon balance

A biomass carbon balance based on the flow of wood-based materials through the glulam process was calculated. Inputs included only wood-based materials (lumber and wood fuel) into the glulam process (lumber manufacturing excluded). Outputs included products and co-products as reported in industry surveys. Emissions related to wood combustion in boilers are also included (FAL 2001). Very little co-product was produced during the production of glulam; therefore, the carbon balance was based on wood carbon only in and out of the glulam process. Table 11 shows wood-related carbon statistics for lumber and wood fuel inputs and associated output air emissions, products, and co-products for the production of 1 cubic meter of

TABLE 11. *Total carbon flow allocated to one cubic meter of glulam obtained from on-site data for the Pacific Northwest (PNW) and Southeast (SE) glulam production regions.*

	PNW	SE
Substance	kg carbon	kg carbon
Inputs		
Green lumber	75	51
Dry lumber	221	285
Wood fuel	18	0
Total inputs	314	337
Outputs		
Air emissions	21	1
Product glulam	244	271
Co-products		
Trimmings	2	31
Shavings	42	27
Wood waste	10	3
Total outputs	319	333

glulam. Lumber inputs included the unaccounted lumber (Table 1), hence making the carbon balance between inputs and outputs within 1.5 and 1.45% for the PNW and SE production regions, respectively. The carbon ratios were obtained from Birdsey (1992) and Skog and Nicholson (1998). The sum of the carbon out of the glulam process (w/ boiler) was 319 kg/m^3 for the PNW and 333 kg/m^3 for the SE region. In the PNW production region, 76% of the carbon was contained in the glulam product, and 17% in co-products. Similar results were produced with the SE glulam production region with 81% of the total carbon output contained in the product and 18% in the co-products. Very little carbon was released in air emissions with only 7% in the Northwest and less than 1% in the SE. Of the 7% released as air emissions for the PNW production region, 97% was from the combustion of wood fuel used in on-site wood boilers. The Environmental Protection Agency (EPA) considers CO_2 emission resulting from wood combustion to be CO_2 impact-neutral; therefore, its contribution to global warming has a net zero effect (EPA 2003).

CONCLUSIONS

The data collected on each glulam production region represented 70 and 43% of the regions' glulam production for the year 2000 for the PNW and SE, respectively. Both cold cure and radio-frequency-cure processes were included in the data obtained. Cumulative energy for glulam production in the PNW region was driven by the lumber drying process, which was generated mostly by wood fuel. Energy from wood fuel and wood waste represented 47% (without co-product) of the cumulative energy for glulam production (including resin and lumber).

In the SE, lumber drying required the dominant amount of energy for processing. All the lumber produced in the SE was dried using wood fuel. Glulam facilities in the SE consumed natural gas for process energy (on-site), which represented about 72% of the total on-site energy and about 42% of the cumulative natural gas consumption.

Electricity use in the PNW glulam production regions was dominated by the lumber and resin production processes, using 45 and 20% of the total electricity, respectively. Although 74% of electricity generation in the PNW is from hydro power plants, the majority of the fuel type to produce electricity for the resin production, obtained from a European producer, was generated primarily from natural gas and crude oil. This emphasizes the need for obtaining domestic resin production data, which would place resin production facilities in closer proximity to composite plants. In the SE production regions, lumber production used 34% of the electrical energy required for glulam production and resin manufacturing used 14%.

The data quality collected from surveys is what can be expected for this industry. Survey reported data on process air emissions differ between glulam manufactures and type of glulam process, cold-cure or radio-frequency processes. Overall, emissions associated with the cold-cure (CC) process were higher than those associated with the radio-frequency (RF) process most likely due to the significantly higher amount of resin used. In addition, data differences between manufacturers were also attributed to the need to dry the lamstock prior to glulam assembly. Standards for glulam production require that the material moisture content cannot exceed 16% at the time of gluing (AITC 1983). The energy differences and subsequent emissions between the two regions reflect the process heating and cooling practices at these facilities.

This work along with similar LCIs on wood-based residential building materials will be accessible through the U.S. LCI database project (NREL 2005). The U.S. LCI database project is a research partnership to develop a publicly available LCI database that will allow LCI practitioners to objectively review and compare data based on similar data collection and analysis methods. As part of Phase I of CORRIM's work plan, the glulam LCI has been peer reviewed and will be accessible to the public for use and informational purposes.

The LCI presented in this paper contains the first LCI on U.S. production of glued-laminated timber from two specified regions. Although concise in its presentation to date, future LCI in this area should emphasize regional boiler emissions for natural gas and wood fuel as well as U.S. resin production information. In this report, resin databases were based on European data, which may not represent regional energy production common in the United States.

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