LIFE-CYCLE ANALYSIS OF WOOD PRODUCTS: CRADLE-TO-GATE LCI OF RESIDENTIAL WOOD BUILDING MATERIALS

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ABSTRACT

This study compares the cradle-to-gate total energy and major emissions for the extraction of raw materials, production, and transportation of the common wood building materials from the CORRIM 2004 reports. A life-cycle inventory produced the raw materials, including fuel resources and emission to air, water, and land for glued-laminated timbers, kiln-dried and green softwood lumber, laminated veneer lumber, softwood plywood, and oriented strandboard. Major findings from these comparisons were that the production of wood products, by the nature of the industry, uses a third of their energy consumption from renewable resources and the remainder from fossil-based, non-renewable resources when the system boundaries consider forest regeneration and harvesting, wood products and resin production, and transportation life-cycle stages. When the system boundaries are reduced to a gate-to-gate (manufacturing life-cycle stage) model for the wood products, the biomass component of the manufacturing energy increases to nearly 50% for most products and as high as 78% for lumber production from the Southeast. The manufacturing life-cycle stage consumed the most energy over all the products when resin is considered part of the production process. Extraction of log resources and transportation of raw materials for production had the least environmental impact.

Keywords: Life-cycle inventory, LCI, wood products, green building materials, cradle-to-gate, energy, emissions.

INTRODUCTION

There is a growing awareness that the manufacturing of any product impacts our environment. Over the past few decades, this has influenced how some consumers buy products and how homeowners, builders, and architects design buildings. Product manufacturers are faced with strict environmental regulations while struggling to meet customers' needs, all while trying to stay competitive in the marketplace. The wood products industry is not exempt from these pressures. Environmental type pressures from the public and government to reduce harvesting, and in some locations to completely quit all forestry operations, are on the rise. This is unfortunate, because the manufacturing of alternative materials to wood can create far greater environmental impacts.

Wood is a renewable resource and "environmentally friendly" compared with other materials (Lippke et al. 2004). The renewable resource aspect can be substantiated when forestry operations are accompanied by third party certification for sustainable management practices. Unfortunately there is a large source of non-technical information available to the public that discourages harvesting and the use of wood products. In a publication by Watershed Media (2001), reference is made several times to the destruction of forest or harvesting old-growth wood in order to build a wood-framed house. To address claims like these, the scientific commu-

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nity world wide has been developing methodology that accurately assesses the environmental impact a product or process my cause over its life cycle.

Life-cycle assessment (LCA) is one approach to accurately assess the environmental burdens associated with the manufacturing of a product from resource extraction to end-of-life. The development of the 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.) an impact assessment phase, and 3.) an improvement phase. By definition, it is an objective process to evaluate the environmental burdens associated with a product, process or activity (Fava et al. 1991). The life-cycle inventory (LCI) conducted in this study presents the quantitative results for several major wood-building materials 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 extraction, production, and transportation of resources for the manufacturing of wood building materials. The LCIs developed are in accordance with the CORRIM Research Guidelines (CORRIM 2001) and the International Organization for Standardization (ISO) protocol for performing life-cycle assessments (ISO 1997, 1998).

Background

Manufacturers of products want to be able to understand the environmental impacts they cause in order to control or reduce them. They do this not only to meet increasing environmental regulations, but to promote their products as environmentally friendly. Every product requires energy to produce it, and many products require a large amount of processing and transport before they reach the consumer. Each process in product manufacturing requires transport, use, maintenance, and finally disposal, all of which use energy that can produce a large variety of emissions with very specific effects on the environment. These processes do not work in a vacuum, but instead are connected with the transfer of inputs and outputs from one process to another making them all interdependent. Environmental impacts created during one process step are embodied within that product as it is transferred to another processing step. It is this systemic approach that is the basis for the LCA methodology.

Life-cycle assessment studies have surfaced over the past decade on the environmental performance of wood products (Arima 1993; ATHENA 1993; Buchanan 1993; Hershberger 1996; Lippke et al. 2004; Perez-Garcia et al. 2005; Richter and Sell 1993). Most of these conducted partial life-cycle inventories and focused only on energy consumption related to raw material extraction and product manufacturing. In addition to an inventory analysis, few performed a life-cycle impact assessment (Perez-Garcia et al. 2005; Lippke et al. 2004). Of the many analyses carried out on wood products, most were conducted prior to development of the LCA framework (Arima 1993; ATHENA 1993; Buchanan 1993; Hershberger 1996; Richter and Sell 1993). Product comparisons of results from these earlier studies have been difficult because of differences in system boundaries, goals and scope, and data quality.

Beginning in 2000, the Consortium for Research on Renewable Industrial Materials (CORRIM) began collecting data to establish LCIs and conduct LCAs on the major structural wood products used in residential construction (Perez-Garcia et al. 2005; Lippke et al. 2004). Data were collected by surveying the wood products industry representing two major wood producing regions in the United States, the Pacific Northwest (PNW) and Southeast (SE). The collected data were a representation of the regional production processes and included all inputs and outputs associated with the growing and harvesting of trees, and the manufacturing of glued-laminated timbers (glulam), softwood lumber, laminated veneer lumber (LVL), softwood plywood, composite I-joists, and oriented strandboard (OSB) (Table 1) (Johnson et al.

TABLE 1. *Annual production totals reported in surveys from the Pacific Northwest (PNW) and Southeast (SE) United States.*

Wood product		Production from survey manufacturers PNW	Production from survey manufacturers SE	% of region's production PNW	% of region's production SE
		Units in million			
Glulam	Board feet	78	60	70%	43%
Lumber	Board feet	862	556	13%	9.4%
LVL	Cubic feet	6.6	7.8	33%	45%
Plywood	Square feet ⅜″ basis	1,233	1,384	26%	14%
OSB	Square feet ⅜″ basis	n/a	1,411	n/a	18%

2004; Kline 2004; Milota 2004; Milota et al. 2004; Puettmann and Wilson 2004; Wilson and Dancer 2004a, 2004b; Wilson and Sakimoto 2004). Growth and yield models of trees, representing conditions in the PNW and SE growing regions, and recent studies of harvesting activities, were used to gather forest regeneration, growth and log production data (Johnson et al. 2004).

All the CORRIM models developed were designed based on a per functional unit product basis, such as a volume measured in board feet or cubic feet. However, traditionally I-joists are measured in linear feet. In the cradle-to-gate analysis presented in this paper, comparisons between products are based on equal volume units; therefore, we chose to not include I-joists in this initial LCI assessment.

In addition to the manufacturing LCIs (gate-to-gate) of wood products, CORRIM used the product environmental profiles to construct two residential homes (Perez-Garcia et al. 2005; Lippke et al. 2004). The analysis was a cradle-to-construction (gate) life-cycle assessment of two residential home designs. Although complete in their scope, lacking was the cradle-to-construction (gate) environmental profiles of each wood product going into the house construction. This study assembled those cradle-to-gate wood product environmental profiles.

The scope of this study details the manufacturing stages of five different wood products used in residential construction from the PNW and SE United States. The PNW region represents forests and wood production practices from Washington and Oregon, and the SE region is a representation of 13 states extending from Virginia to Texas (Fig. 1). Due to the strict confidentiality that CORRIM adhered to for the cooperating manufacturers, the SE wood product manufacturing region presented in Fig. 1 represents every state that contributed data to one or all of the products assessed.

This study documents cradle-to-gate LCIs of glulam, softwood lumber, laminated veneer lumber (LVL), softwood plywood, and oriented strandboard (OSB) based on resources from the PNW and SE United States. The LCI results consider four life-cycle stages: regeneration and harvesting, product manufacturing, resin manufacturing, and transportation. Primary data were collected in the form of production data and fuel used for each wood production process, while secondary data in the form of fuel use and emissions to produce energy and electricity and all transportation and resin production were obtained from available databases (Athena 1993; Boustead 1999; EIA 2001; EPA 2003; FAL 2001; Nilsson 2001; PRé Consultants 2001).

The cradle-to-gate model development

Product LCIs encompassing a gate-to-gate (manufacturing life-cycle stage only) system boundary were previously performed for each wood product and forestry operation from both regions (Johnson et al. 2005; Kline 2005; Milota et al. 2005; Puettmann and Wilson 2005; Wilson and Sakimoto 2005; Wilson and Dancer 2005). A single unit process approach was taken in modeling the LCIs for glulam and LVL, while a

FIG. 1. Survey regions for the production of glued-laminated timbers, lumber, laminated veneer lumber, plywood, and oriented strandboard produced in the Pacific Northwest and Southeast regions of the United States.

multi-unit process approach was modeled for lumber, plywood, and OSB. For specific process descriptions see individual CORRIM reports for each.

The cradle-to-gate models presented are an integration of five single gate-to-gate LCIs for each production region giving ten cradle-to-gate assessments for the five products. The integrated models each contain four life-cycle stages within the cradle-to-gate cumulative system boundary: harvesting, manufacturing, resin production, and transportation of logs, resin, and materials to the wood products manufacturers (Fig. 2). The product stage life-cycle inventories link the indi-

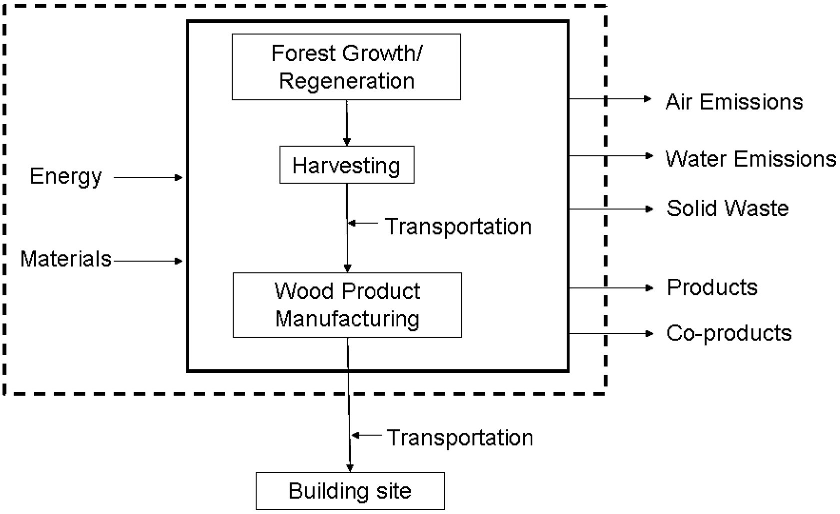

FIG. 2. System boundary (dotted lines) for cradle-to-gate analysis of the production of structural wood products in the Pacific Northwest and Southeast United States.

vidual LCIs with forestry operations from the respective region and link each life-cycle stage with a transportation process based on data contained in each product report. The analysis of the integrated model was performed using SimaPro5, a life-cycle assessment software package (PRé Consultants 2001).

The functional unit for all products is referenced to one cubic meter of each product (Table 2). The product weight includes resin where applicable and is on an oven-dry basis. All input and output data within the cumulative system boundary were allocated to the functional unit of product and co-products in accordance with International Organization for Standardization (ISO 1997, 1998). All allocations of environmental burdens were based on the mass of products and co-products per unit volume.

The system boundary encompasses each product manufacturing process including material (logs, wood, resin, fuels) transport to each production facility. Transportation distances were reported in surveys and used to calculate product transported per kilogram–kilometers (kg-km). The cumulative system boundary includes all upstream flows of energy, fuel, and raw material production.

Energy consumed during transportation between the harvesting life-cycle stage and manufacturing accounts for actual distances reported from each production region (Fig. 2; Table 3). Excluded from transportation is the distance between product manufacturing and the construction site. Raw material transportation distances were reported by contributing wood products producers and are actual distances of raw material transport to the facility. These distances can be found in the 2004 CORRIM reports (Johnson et. al 2004; Kline 2004; Milota 2004, Milota et al. 2004; Puettmann and Wilson 2004; Wilson and Dancer 2004b; Wilson and Sakimoto 2004). Product moisture contents used (oven-dry basis) at the time of shipping were 60% and 100% for PNW and SE logs, respectively, 60% for green lumber, 17% for kiln-dried lumber, plywood, OSB and LVL were 5%, and glulam at 10%.

To determine the transportation impact from the manufacturing site to the residential construction site, transportation distances are given on a per kilometer basis for both rail and road modes of transportation (Table 3). If the reader would like to determine the energy consumed for transportation of a product to a specific construction site, these transportation data (Table 3) would be multiplied times the shipping distance from the plant to the construction site, and added to the cumulative energy consumed for transportation provided in this study. Meil et al. (2004) reported transportation distances for the various wood products to the two building sites in Minneapolis, Minnesota, and Atlanta, Georgia. Wood products for the Minneapolis house were transported by rail from the PNW production region to a distribution center and then by road to the construction site, except for OSB which used SE manufacturing data, but was transported locally from a Midwest distribution center (Meil et al. 2004). Wood products used in the Atlanta house were transported directly from the SE region to the construction site. Since these modes of travel and travel destinations were hypothetical, we chose to keep the product transportation to the construction site on a per kilometer basis so calculations can be made based on actual distances. For example: softwood lumber was transported 2,538 km by rail to a distribution center in Minnesota; then the lumber was transported by road to the construction site at a distance of 60 km. Therefore, using the energy transportation factors from Table 3: 0.13 MJ/m^{3}km × 2,538 km = 330 MJ/m^3 for rail transport and 0.24 MJ/m^{3}km × (60 km × 2)(use round trip for road transport) = 29 MJ/m^3 for road. The total transportation energy value for kiln-dried lumber from cradle-to-construction site is 506 MJ/m^3.

TABLE 2. *Product weights (oven-dry basis) for functional units used in the LCIs.*

Product	PNW	SE
	kg/m^3	
Glulam	484	551
Lumber, KD	413	510
Lumber, green	413	—
LVL	529	606
Plywood	480	555
OSB	—	651

Table 3. *Harvesting-to-building site transportation cumulative energy allocated to one cubic meter of wood product from the Pacific Northwest (PNW) or Southeast (SE) production region.*

	PNW					SE				
	Glulam[4]	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber, KD	LVL	Plywood	OSB
	MJ/m^3					MJ/m^3				
Harvesting-to-manufacturing (actual survey distances)[1,2]	161	147	113	112	90	391	114	219	196	390
Manufacturing-to-building site (per kilometer basis)	MJ/m^{3}km					MJ/m^{3}km				
Rail[3]	0.12	0.13	0.18	0.15	0.11	—	—	—	—	—
Road[1]	0.23	0.24	0.32	0.28	0.21	0.26	0.26	0.30	0.28	0.34

[1] Energy factors are based on roundtrip distances with an empty back-haul. No rail transport included.
[2] 100% road transport
[3] Energy factors are based on one-way trip distances with no back-haul
[4] Includes log lumber transport

LCI DATA OF WOOD AS A BUILDING MATERIAL

Environmental performance was measured based on resource use, energy requirements, and emissions to air, water, and land. Comparisons were made between harvesting, product manufacturing, resin production (where applicable), transportation, and between products on their environmental performance.

From the LCI data, energy use and emissions to air, water, and land were assessed for the production of glulam, softwood lumber, LVL, softwood plywood, and OSB (Tables 4–8). The data represent average regional data from the PNW and SE United States for the production years specified in the CORRIM reports (Johnson et. al 2004; Kline 2004; Milota 2004, Milota et al. 2004; Puettmann and Wilson 2004; Wilson and Dancer 2004b; Wilson and Sakimoto 2004). Raw material supply for all products including OSB is based on virgin fiber from each production region. It should be noted that these numbers are not static; manufacturing practices and technology are constantly changing. These data are a representation of the industry from two geographical regions for specific production years; nevertheless, the results do show some general tendencies shared among the wood products industry as whole.

Energy consumption

Regeneration and harvesting have a minimal environmental impact (less than 5%) on the production of each product when considering a

Table 4. *Cradle-to-gate, cumulative energy[1] (MJ/m^3) allocated to one cubic meter of structural wood products manufactured in the Pacific Northwest (PNW) and Southeast (SE) regions. Electricity production is included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber, KD	LVL	Plywood	OSB
	MJ/m^3					MJ/m^3				
Harvesting	147	143	139	148	148	213	203	189	206	217
Product manufacturing	4,650	3,415	295	3,670	2,700	5,056	3,175	4,700	4,227	7,412
Resin production	409	0	0	755	699	584	0	1,048	1,021	3,126
Transportation[2]	161	147	113	112	90	391	114	219	196	390
TOTAL	5,367	3,705	548	4,684	3,638	6,244	3,492	6,156	5,649	11,145

[1] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, diesel 44.0, liquid petroleum gas 54.0, natural gas 54.4, crude oil 45.5, oven dry wood 20.9, and gasoline 48.4. Energy from uranium was determined as 381,000 MJ/kg and electricity at 3.6 MJ/kWh.
[2] Transportation of logs and other materials to production facilities.

TABLE 5. *Cradle-to-gate cumulative energy*[1] *requirements by fuel source (MJ/m^3) allocated to one cubic meter of structural wood products produced in the Pacific Northwest (PNW) and Southeast (SE) regions. Fuels for electricity production are included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber, KD	LVL	Plywood	OSB
	MJ/m^3					MJ/m^3				
Coal	210	92	49	198	132	854	356	857	676	1,270
Crude oil	534	361	274	706	486	916	337	812	756	1,883
Natural gas	1,957	1,447	108	1,559	898	2,013	279	2,156	1,536	3,809
Uranium	30	7	4	15	10	84	35	63	50	114
Biomass	2,258	1,595	0	1,741	1,800	2,344	2,473	2,205	2,573	3,951
Hydropower	376	200	111	459	308	21	4	45	43	98
Electricity other	2	3	2	7	5	11	8	18	15	20
TOTAL	5,367	3,705	548	4,684	3,638	6,244	3,492	6,156	5,649	11,145

[1] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, natural gas 54.4, crude oil 45.5, and oven-dry wood (biomass) 20.9. Energy from uranium was determined at 381,000 MJ/kg and electricity at 3.6 MJ/kWh.

TABLE 6. *Cradle-to-gate cumulative emissions to air allocated to one cubic meter of structural wood products produced in the Pacific Northwest (PNW) and Southeast (SE) production regions; includes all life-cycle processes from forest regeneration through wood products production. Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber	LVL	Plywood	OSB
	kg/m^3					kg/m^3				
CO	2.00	1.43	0.22	1.29	1.24	2.07	1.83	1.78	1.90	1.79
CO_2 (biomass)	230	160	0.01	141	146	231	248	196	229	378
CO_2 (fossil)	126	92	27.13	87	56	199	62	170	128	294
HAPS	0.20	0.01	0.00	0.13	0.11	0.01	0.01	0.11	0.22	0.41
Methane	0.28	0.19	0.02	0.22	0.13	0.40	0.10	0.41	0.30	0.70
NO_2	0.92	0.67	0.31	0.69	0.57	1.26	0.64	1.11	0.95	1.52
Particulates	0.57	0.05	0.03	0.34	0.33	0.19	0.05	0.60	0.41	0.37
Particulates (unspecified)	0.04	0.01	0.01	0.02	0.01	0.09	0.04	0.09	0.07	0.12
SO_2	1.36	1.03	0.12	1.14	0.67	1.78	0.43	1.90	1.41	3.09
VOC's	0.31	0.08	0.03	0.32	0.34	1.14	0.49	0.04	0.16	1.06
Total	361.68	255.47	27.88	232.15	205.40	436.94	313.59	372.04	362.42	681.06

cradle-to-gate analysis as a percentage of total energy consumption (Table 4).

The main energy use is in the manufacturing life-cycle stage and is consumed mainly during drying of lumber and veneer, and final pressing of composite products (Table 4). Up to 92% of the total manufacturing energy was used for kiln-drying (KD) softwood lumber in the PNW and 91% in the SE (which is always KD). When the energy for producing resins is included in the manufacturing energy, all the building materials (except for green lumber) consumed over 90% of the cumulative cradle-to-gate energy during product manufacturing.

The cumulative manufacturing energy for green lumber produced in the PNW is 548 MJ/m^3 compared to KD lumber with a total energy of 3,705 MJ/m^3 (Table 4). The manufacturing life-cycle stage for green lumber was only 50% of the total cradle-to-gate energy. In the West it a common practice to use green lumber (lumber that has not been dried) for framing, while in the SE all the lumber is KD. Since most of the energy consumed during lumber manufacturing is

TABLE 7. *Cradle-to-gate cumulative emissions to water allocated to one cubic meter of structural wood products produced in the Pacific Northwest (PNW) and Southeast (SE) production regions; includes all life-cycle processes from forest regeneration through wood products production. Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber	LVL	Plywood	OSB
			kg/m^3					kg/m^3		
BOD	0.0037	0.0015	0.0002	0.0016	0.0010	0.0046	0.0004	0.0022	0.1552	0.0067
Cl−	0.0793	0.0643	0.0048	0.0691	0.0398	0.0788	0.0131	0.0958	0.0015	0.7186
COD	0.0476	0.0203	0.0018	0.0168	0.0100	0.0578	0.0042	0.0212	0.0398	0.0562
Dissolved solids	1.7597	1.4205	0.1112	1.5230	0.8794	1.7685	0.2914	2.1001	0.0267	3.3624
Oil	0.0309	0.0251	0.0021	0.0272	0.0158	0.0309	0.0053	0.0375	0.8555	0.0594
Suspended solids	0.0597	0.0306	0.0048	0.0274	0.0175	0.1061	0.0254	0.0686	0.0156	0.1136
Total	1.9807	1.5622	0.1250	1.6651	0.9635	2.0466	0.3397	2.3253	1.0943	4.3170

TABLE 8. *Cradle-to-gate cumulative emissions to land allocated to one cubic meter of structural wood products produced in the Pacific Northwest (PNW) and Southeast (SE) production regions; includes all life-cycle processes from forest regeneration through wood products production. Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber	LVL	Plywood	OSB
			kg/m^3					kg/m^3		
Inorganic general	0.69	0.67	0.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Paper/board packaging	0.08	0.08	0.05	0.00	0.00	0.35	0.33	0.00	0.00	0.00
Solid waste	10.93	5.31	1.25	6.74	4.45	21.95	8.21	26.99	24.12	27.18
Wood	0.01	0.01	0.05	0.00	0.00	0.24	0.23	0.00	0.00	0.00
Total	11.75	6.06	1.91	6.74	4.45	22.53	8.76	26.99	24.12	27.18

in the drying process, it would be expected that the energy required to produce green lumber would be considerably lower—85% lower when considering the cumulative cradle-to-gate analysis.

Weight of product has a significant effect on impacts associated with transportation as denoted by increased requirement for coal and crude oil (raw resource for diesel production) used for green lumber production (Table 5) and the associated CO_2 emission (Table 6).

Type of fuel source used for electricity production also plays an important role in determining environmental impacts of a product. Since the manufacturing of most products uses electricity, understanding the type of fuel used helps in the development of the environmental burdens associated with energy consumption. This became especially significant when comparing wood product production from the PNW and SE regions. The greater use of fossil-based fuels such as coal and crude oil in the SE (Table 5) is linked directly to an increased amount of fossil-based carbon dioxide released into the atmosphere (CO_2 fossil) (Table 6). Electricity production in the SE region used 46% of the fuel source from coal while nearly 72% of the total fuel used for electricity production was fossil-based (EIA 2000). This is in contrast to the PNW, where 74% of the fuel used for electricity production came from hydro-power.

In the PNW regions, the main single fuel source for all products was from biomass, which represented a minimum of 37% in LVL production and up to 49% in plywood manufacturing (Table 5). Natural gas made up the majority of the remainder of fuel consumption ranging from 20 to 39% over all products from the PNW region; while in the SE wood products production region, the main fuel source came from biomass and natural gas with the exception of kiln-dried lumber, 70% of the fuel use was from biomass, where nearly 100% of that was used for wood drying.

Overall, the substitution of the biomass fuels with fossil-based fuels would have a significant impact on emissions released and resource use. Since both regions currently use a considerable amount of biomass fuel in the production of wood products, any additional substitutions would have to be in the resin production processes. This alone would pose a huge challenge, since the use of biomass in the wood products industry is primarily because it is self-generated on-site during manufacturing. If biomass became unavailable, the wood products industry would also have to use an alternative fuel source, which would most likely be natural gas. The fact that biomass fuel is renewable cannot be disregarded when its substitution would be a fossil-based, non-renewable resource, i.e. natural gas combustion emissions contribute to global warming.

Energy consumed for transportation of raw materials to the wood product facilities represents less than 6% for all products, with the majority around 4% of total energy (Table 4). The exception is the transportation impact for green lumber, where energy requirement represents nearly 21% of the total energy as a result of its heavier weight (green weight) and its lower overall energy use to produce. It was assumed that the green lumber shipping moisture content was 60% oven-dry basis.

Resin production consumed 8, 16, and 19% of the total energy for glulam, LVL, and plywood, respectively from the PNW regions. Energy for resin production of OSB consumed 28% of the total energy. The main resins used were phenol-formaldehyde (PF) (ATHENA 1993) used for plywood and LVL, phenol-resorcinol-formaldehyde (PRF) and melamine-urea-formaldehyde (MUF) used for glulam (Nilsson 2001), and methylene-diphenyl-diisocyanate (MDI) and PF for OSB (Boustead 1999; ATHENA 1993). When comparing resins to wood products, they have a significantly higher consumption of non-renewable resources while wood products use a considerable amount of renewable resources from wood fuel and log resources. In resin production, non-renewable energy is consumed for feedstock (natural gas, crude oil), and production energy (natural gas, electricity).

The substitution of LVL or glulam timbers for solid-sawn lumber reflects an increased use in energy (Tables 4 and 5) and subsequent emissions released (Table 6), primarily due to the use of resin and the extra processing needed for composite production (finger-jointing, pressing). These differences are more pronounced in the SE production models. On the other hand, with the increasing amount of smaller diameter logs for lumber production, these composite products provide a viable substitution with little increase in environmental impacts especially when comparing products from the PNW. Also, with the development of U.S. resin databases, the differences in energy use between solid-sawn lumber and composite products, such as glulam timbers and LVL, may be reduced.

Emission to air, water, and land

Carbon dioxide (CO_2) emission on a mass basis was the greatest emission released over all life-cycle stages (Table 6). Carbon dioxide released from combustion of wood fuel or biomass is denoted as CO_2 (biomass), where CO_2 fossil is a result of combustion of fossil-based fuels such as natural gas, diesel, and gasoline. CO_2 (biomass) emissions made up the major carbon dioxide component except for the production of green lumber. According to the Environmental Protection Agency, CO_2 emissions as a result of biomass combustion do not contribute to global warming; they are considered as being CO_2 neutral (EPA 2003).

In general, a higher amount of CO_2 fossil-based emissions were generated from the SE production region compared to the PNW industry emissions due to the increased use of natural gas in those local industries and to fuel type for electricity generation. In the PNW, electricity generation was dominated by hydro-power (EIA 2001), and in the Franklin database there are no impacts (no CO_2) for this type of electricity generation.

Total water and land emission had tendencies to be higher if the product required a resin additive (the composites); the same trend seen in energy consumption. The exception being plywood. This exception can be explained by the nature of the plywood resin database (ATHENA 1993), there was a limited amount of resource use (feedstock energy) and subsequent emission included in this database, whereas the resin databases used for glulam and OSB had very extensive input and output data associated with the production of PRF, MUF, and MDI resins (Boustead 1999; Nilsson 2001). There is work started in the CORRIM Phase II research plan to include the LCIs of resin production from the United States. Other inconsistencies between products, mainly seen in solid waste results, can be attributed to the data reported from the individual wood products industries (Table 8).

DISCUSSION

Most environment assessments performed on wood products have occurred in other countries, primarily Europe and Canada (ATHENA 1993; Buchanan 1993; Richter and Sell 1993). Results from this study for glulam have similarities to a LCI conducted at the Swiss Federal Laboratory for Materials Testing and Research (EMPA) (Richter and Sell 1993) (Table 9). It should be noted that higher heat values for fuel conversions were used in this study, while this is unknown for the EMPA study. As noted earlier, making comparisons between this study and previous studies on other wood products would be difficult due to differences in system boundaries, and goals and scope of the studies, so only glulam comparisons can be made.

The cradle-to-gate LCIs presented here are part of CORRIM Phase I research plan and is the first to profile wood products produced in the United States. The results here and as well as results from previous LCIs on wood products show the same general trend, consistently showing that wood products manufacturing consumes significantly less energy than the manufacturing of non-wood alternatives (Arima 1993; ATHENA 1993; Buchanan 1993; Lippke et al. 2004; Perez-Garcia et al. 2005; Richter and Sell 1993). Another commonality between these wood product LCIs is the increased energy demand if the product production requires additives such as resin and wax, and operations requiring the generation of heat. So if any improvements in energy conservation should occur in wood products production, focus should be on low energy drying processes, low energy or faster hot-pressing processes, reduced or alternative feedstocks for resin manufacturing as well as reduced production energy. In addition, since all wood product operations require energy use, the type of fuel source should be considered. Fossil-based fuels will emit greater amounts of emissions that contribute to global warming, ozone depletion, resource depletion, and more (EPA 2005). While non-fossil-based, renewable fuels such as biomass can have many benefits such as reduced fuel loads on managed forest lands, reduction in wood waste that would traditionally end up in a landfill (EPA 2000), and a reduction in global warming emissions since CO_2 emitted from biomass combustion is considered carbon neutral (EPA 2003).

TABLE 9. *Energy consumption comparisons for glued-laminated timbers comparing PNW results from this paper and a study by Richter and Sell (1993).*

Glulam MJ/m^3	Puettmann and Wilson 2005[1]	Richter and Sell 1993[2]
Harvesting	147	150
Product manufacturing	4,650	5,210
Resin production	409	540
Transportation	161	100
TOTAL	5,367	6,000

[1] Energy value were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, diesel 44.0, liquid petroleum gas 54.0, natural gas 54.4, crude oil 45.5, oven-dry wood 20.9, and gasoline 48.4. Energy for uranium was determined at 381,000 MJ/kg and electricity at 3.67 MJ/kWh.

[2] Energy value conversions used are unknown.

CONCLUSIONS

The life-cycle inventory of wood building products reported in this study was the first in

U.S. to consider a cradle-to-gate scope. Environmental performance of these products was measured by total energy and major emissions. LCI findings for the production of wood products, by the nature of the industry, show that when they use biomass (wood waste) as the major fuel source, it significantly lowers the environmental impact when assessed by the type of emissions released into the atmosphere (CO_2 biomass versus CO_2 fossil). This was more pronounced in the PNW production region than in the SE. Harvesting and transportation produce the least burdens, while operations requiring heat generation produce the greatest. Resin production can consume a large amount of energy for both feedstock and production, but these findings are based on European databases that use different electricity production sources. Work is underway to develop a U.S. resin life-cycle inventory database that would reflect local fuel use for feedstocks, production, electricity generation, and transportation of materials used to manufacture resins for wood composite products.

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