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

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ABSTRACT

A life-cycle inventory (LCI) study is conducted of softwood plywood manufacturing. This gate-to-gate study includes all materials, fuels, and electricity inputs to produce plywood, co-products and emissions. Data were collected through surveys of manufacturing facilities in the Pacific Northwest and the Southeast. SimaPro software, a program to conduct life-cycle inventory studies, is used to process the data and determine environmental impacts in terms of material use and emissions. The data are allocated on a mass basis to plywood based on their contribution to the mass sum of all product and co-products. All data are provided on a production unit basis of 1.0 m^3 and 1.0 MSF 3/8-inch basis, the U.S. industry standard. In addition to LCI data, carbon flow data are also given. The LCI data are publicly available through reports, this publication, and the U.S. LCI Database Project. The data are useful for generating cradle-to-gate product LCIs when combined with the LCIs to produce logs for the mills and material transportation impacts, and are useful as a benchmark for assessing process performance, for conducting life-cycle analysis of wall, floor, and roof assemblies consisting of plywood and other products, and of residential structures.

Keywords: Life-cycle inventory, LCI, softwood plywood, building materials, carbon balance, energy use, emissions.

INTRODUCTION

Background

Softwood plywood has had a long tradition as a structural building material for both commercial and residential construction. Plywood is used as structural sheathing for roof, wall and flooring, and for sub-flooring applications in home construction. This study focuses on production practices in the Pacific Northwest and Southeast, production centers of the softwood plywood industry in the U.S. Plywood is produced by peeling logs into veneer sheets and dried; phenol-formaldehyde resin is then applied to the dried sheets, which are normally stacked with alternating grain orientation. The stack is put into a hot press where pressure and heat are used to provide contact and curing, and the cured panel is then removed and sawn to standard sizes, e.g., 1.22 × 2.44 m (4 × 8 ft) sheets being the most common. Plywood is made from various species; in the Pacific Northwest region, it is made primarily from Douglas-fir and western hemlock, with other species such as spruce and western larch also used; and in the Southeast, it is made from a group of wood species referred to as southern pine, with the dominant species in this group being slash and loblolly pine. The total softwood plywood production in 2000 for the U.S. was 15,464,000 m^3 (17,475,000 thousand square feet (MSF) 3/8-inch equivalence) (APA 2001). This production represents 59% of structural panel production in the U.S., with the remainder being oriented strandboard (OSB).

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The U.S. produces enough softwood plywood, if it were all sheathing, to build about 2,813,000 homes annually based on NAHB (2001) at 5.50 m^3 (6.212 MSF 3/8-inch equivalence) of sheathing per home.

The goal of this study was to document the life-cycle inventory (LCI) of manufacturing softwood plywood. LCI involves the collection and quantification of all inputs and outputs for a given product through its life cycle. This study specifically examines those inputs and outputs for the manufacturing operation and is referred to as a gate-to-gate study. This study is part of the Consortium for Research on Renewable Industrial Materials (CORRIM) Phase I project to study the life-cycle assessment of renewable building materials (Bowyer et al. 2004; Lippke et al. 2004; Perez-Garcia et al. 2005). The LCI data of this study can be used by practitioners of LCI and life-cycle assessment (LCA) of the product and its use in buildings in an overall cradle-to-grave analysis. The data are also available in the U.S. LCI database (2005). A survey was conducted of a representative sample of manufacturers in the two production regions to provide primary data for the analysis. Secondary data were obtained for impacts associated with the manufacture and delivery of electricity and all fuels (Franklin Associates Ltd 2001; PRé Consultants 2001; USDOE 2001), CO_2 and press emissions (EPA 2001), and the production of phenol-formaldehyde resin (ATHENA 1993).

Scope of study

The annual production of mills in the two regions ranged from 44,245 to 398,205 m^3 (50,000 to 450,000 MSF). This study collected data from representative mills that would be considered in the mid- to upper-portion of this range. Five mills from each of the two regions provided data for 2000 in terms of plywood and co-product production, raw materials, electricity and fuel use, and emissions. In 2000 the total annual softwood plywood production for the Pacific Northwest region was 4,146,641 m^3 (4,686,000 MSF) with the mills providing data representing 26% of production, and in the Southeast the total production was 8,705,646 m^3 (9,838,000 MSF) with the mills providing data representing 14% of production (APA 2001). The states covered in the Pacific Northwest region included Oregon and Washington, and in the Southeast region included Alabama, Georgia, Louisiana, Mississippi, Florida, Arkansas, and Texas. For a cradle-to-gate analysis, these data would need to be combined with the impacts for the resource module that generated logs, and the transportation impacts for delivery of logs, bark, veneer, and resin to the plywood mill.

Critical external reviews of this LCI process and analysis were conducted to ensure compliance with CORRIM and ISO 14040 and 14041 protocol (CORRIM 2001; ISO 1997; ISO 1998). Complete details of this study for plywood production and the overall CORRIM project can be found in Wilson and Sakimoto (2004) and Bowyer et al. (2004), respectively.

Plywood process and description

The plywood process was broken down into six unit processes rather than examining the process as a "black box." The rationale for taking this approach is that a unit process type of model would be most useful in analyzing ways to improve process efficiency, optimize operations, and reduce environmental impacts. The data in this format could also be used as a benchmark to document process improvements. Furthermore, the unit process approach provides a more realistic assigning of environmental burdens than the black-box approach especially since a high percentage of co-products (about 50% by weight of output product and co-products) are produced. This approach also allows unit processes developed for one process to be used for modeling other processes. The inputs into the plywood process include logs with bark, energy as electricity or fuels, resin, water, and ancillary materials. The outputs include plywood, co-products (bark, chips, peeler core, clippings, green veneer, downfall, trim, and sawdust that are defined as sold outside the system boundary), and emissions to air, land, and water. The unit processes used to model softwood plywood production are shown in Fig. 1. The following are descriptions of the unit processes to consider:

1. *Debarking and bucking.* This unit process includes mechanically removing the bark from the logs and cutting them to the proper length to make wood "blocks" for peeling. Co-products generated include bark and some wood waste. Inputs include electricity to operate equipment and diesel fuel for the log haulers.
2. *Conditioning.* The wood blocks are heated with either hot water or direct steam to improve the quality of peeled veneer. There are no co-products and the inputs include steam and electricity.
3. *Peeling and clipping.* Blocks are peeled in the lathe to make long ribbons of veneer that are clipped to size, and sorted by moisture content in preparation for drying. Co-products include roundup wood, peeler cores, veneer clippings and trim. The inputs include electricity to operate the lathe and conveyor.
4. *Veneer drying.* Veneers are dried in continuous dryers from moisture contents of 25–100% down to 3–5% moisture content (oven-dry basis). This is the most energy-intensive unit process and uses various heat sources. Co-products include veneer downfall and other wood waste. Air emissions occur as the wood elevates in temperature and the wood dries. Because of high temperatures of the wood, this process is a primary source of emissions of volatile organic compounds (VOC). Emissions can also be due to the direct combustion of natural gas or wood and bark hogged fuel at the dryers. Emissions also occur at the hogged wood fuel boiler that provides steam to the dryers.
5. *Lay-up and pressing.* Veneers are coated with phenol-formaldehyde resin and stacked into panels for hot-pressing. Heat and pressure are used in the press to cure the resin, thereby bonding the veneers to make plywood. There are no co-products for this unit process. Emissions included those from the wood at elevated temperatures and the curing of the phenol-formaldehyde resin. Emissions also occur at the boiler that provides steam to heat the plywood hot press.

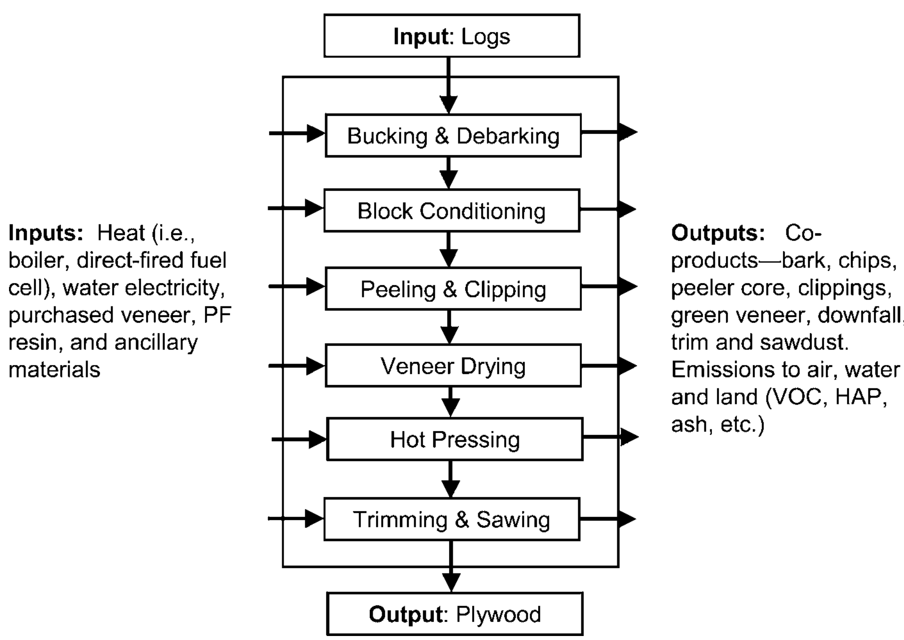

FIG. 1. Unit process approach to the modeling of the plywood manufacturing process.

6. *Trimming and sawing.* Plywood panels coming out of the press are sawn to appropriate dimensions, usually 1.22 × 2.44 m (4 × 8 ft). Co-products include plywood trim and sawdust. Emissions include a small amount of particulate.

Functional unit

The functional unit for plywood is one cubic meter (1.0 m^3) or one thousand square feet of 3/8-inch equivalent volume (1.0 MSF), the U.S. industry practice. For conversion of units from the U.S. industry measure, 1.0 MSF is equal to 0.8849 m^3. All input and output data were allocated to the functional unit of product based on the mass of products and co-products in accordance with CORRIM and International Organization for Standardization (ISO) protocol (CORRIM 2001; ISO 1997; ISO 1998).

System boundaries

The general system boundary for the LCI covers plywood manufacturing and its associated processes (see Fig. 2). The system boundary (solid line box) includes the impacts due to the manufacture of plywood, the production, delivery, and combustion of fuels, the generation of electricity, and the manufacture of resin. This study refers to the environmental impacts in this system boundary as the cumulative impacts. Excluded are the impacts for the growing, harvesting, and transportation of logs and the transportation of resin and purchased veneer and hogged wood fuel. The cumulative system boundary considers both the off-site and on-site emissions. A second system boundary (dotted line box) is used when considering only the site-generated emissions. This second boundary excludes emissions to manufacture and deliver logs, fuels, electricity, and resin. In this case, these materials are reported in their physical units.

Assumptions

The data collection, analysis, and assumptions followed protocols as defined in "Consortium for Research on Renewable Industrial Materials (CORRIM)—Research Guidelines for Life Cycle

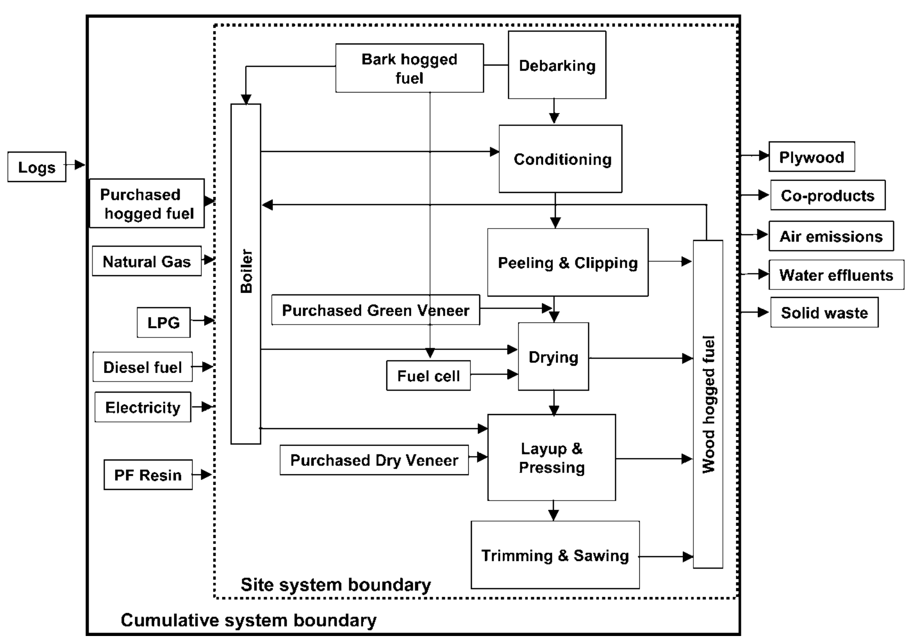

FIG. 2. System boundaries for both the cumulative and mill site for modeling the plywood manufacturing process.

Inventories" dated April 18, 2001 (CORRIM 2001). Additional considerations include:

- All data from the mill surveys were weight-averaged for the five mills in each production region based on their individual production to provide a "composite" mill representative of each region. Where appropriate, missing data from various mills were not included in weight averages.
- The purchase of dry and wet veneers comes with the same allocated burdens as if produced in the mill since they use the same unit process models. The additional burden for transportation of the veneers is handled separately using the delivery mileage data.
- Data quality was high based upon comparisons between mills and regions, and on mass and heat balances. Inconsistent data were addressed by contacting mill personnel to resolve the issue.
- Density values for the wood species used to make the plywood were obtained from Wood Handbook—Wood as an Engineering Material (Forest Products Laboratory 1999), and based on their weighted percentage of use as reported by manufacturers; the weighted average density was calculated to be 437 kg/m^3 (27.26 lb/ft^3) oven-dry, wet volume for Pacific Northwest species and 505 kg/m^3 (31.51 lb/ft^3) for Southeast species.
- Log inputs were provided in thousand board feet (Mbf) in Scribner scale for the Pacific Northwest and in Doyle scale for the Southeast and converted to ft^3 and m^3.
- All conversion units for forestry and forest products type conversions were taken from Briggs (1994).

SimaPro 5.0.009, a software package designed for analyzing the environmental impact of products during their whole life cycle, was used to perform the life-cycle inventories (PRe' Consultants 2001). Developed in the Netherlands by PRé Consultants B.V., SimaPro5 contains a U.S. database by Franklin Associates (FAL 2001) for a number of materials, including fuels, electricity, and chemicals.

MATERIAL FLOWS

Environmental burdens associated with the transportation of resources to the mill were not included for the delivery of logs, bark on logs, purchased veneer, purchased hogged fuel, and resin. All deliveries to the mills were made by truck. Table 1 provides the one-way delivery distances for each of these materials. For any environmental impact analysis, the return haul for the trucks should be considered empty.

The flow of wood in and out of the plywood process for a mass balance is given in Table 2. The values consider wood only and do not include the weight of the bark. The recovery efficiency for the Pacific Northwest (PNW) and Southeast (SE) production regions based on the wood portion of plywood compared to the input wood in logs to the mill was approximately the same for both regions at 50.6% and 50.3%, respectively. The densities of PNW wood species of Douglas-fir (*Pseudotsuga menziesii (Mirbel) Franco*) and western hemlock (*Tsuga heterophylla*) are less than those for SE southern pine, which are mainly comprised of loblolly pine (*P. taeda* L.) and slash pine (*P. elliottii* Engelm.). As such, to produce 1.0 m^3 (or to produce 1.0 MSF; the following values in parentheses are all on a per 1.0 MSF basis) of plywood, it took 917 kg and 1,066 kg (1,788 lb and 2,080 lb) of logs without bark for the PNW and SE regions, respectively. The mills to meet their total wood use purchased a small quantity of both dry and wet veneer. The mass balance of wood in and out was fairly close, with only 7.6% less wood going out than coming in for the PNW, and a near perfect balance for the SE mills. The 7.6%

TABLE 1. *Delivery distance (one-way) for materials to plywood mill.*

	Pacific Northwest delivery distance		Southeast delivery distance	
Material delivered to mill	km	Mile	km	Mile
Logs (roundwood)	97	60	156	97
Bark on logs	97	60	156	97
Purchased veneer	121	75	246	153
Purchased wood fuel	89	55	103	64
Phenol-formaldehyde resin	196	122	158	98

TABLE 2. *Wood mass balance for production of a unit of plywood. All weights are reported on an oven-dry basis.*

	PNW plywood		SE plywood	
	kg/m³	lb/MSF	kg/m³	lb/MSF
Inputs				
Logs without bark[1]	917	1,788	1,066	2,080
Purchased dry veneer	3.1	6	4.20	8.07
Purchased green veneer	7.2	14	5.30	10.40
Total	927	1,809	1,075	2,098
Outputs				
Plywood (wood only)[2]	470	916	541	1,055
Wood chips	218	425	331	645
Peeler core	49	95	57	112
Green clippings	16	31	89	173
Veneer downfall	1.7	3.4	0	0
Panel trim	55	107	31	61
Sawdust	4.9	9.6	2.2	4.2
Wood waste to boiler	0.13	0.25	16	30
Sold wood waste	11	21	11	21
Sold dry veneer	32	63	0	0
Unaccounted wood[3]	70	137	−1.4	−2.64
Total	927	1,809	1,075	2,098

[1] The weights are based on survey log volumes and the average species density of wood.
[2] Based on the weight of plywood minus the survey reported amount of resin.
[3] Used to balance the input and output wood flow for mills.

for the PNW represented 70 kg (137 lb) of wood; a significant portion of it, 48 kg, was most likely used as hogged wood fuel for the boiler. The overall allocation of environmental burdens was based on the mass of the product and co-products. The actual burdens for the co-products are somewhat different than simply listed by a single mass-allocation value and the environmental impacts for the entire manufacturing process, as would be the case for a black-box approach. For a unit process approach, burdens are assigned at each unit process which means that the burdens are based on their mass allocation at the unit process, level and the environmental impacts up to the specific unit process where the co-product was generated; e.g., green clippings would differ from panel trim since the latter would also include allocated burdens for dryer and hot-press emissions and the resin. The allocated burdens to plywood using a unit process approach provide a more realistic approach than using a black-box approach. For example, for a unit process approach about 70% of the CO_2 emissions are allocated to plywood, whereas in a black-box approach about 50% of the CO_2 would be allocated.

To produce 1.0 m^3 (or to produce 1.0 MSF) of plywood in the Pacific Northwest, the mills needed 917 kg (1,788 lb) of wood in the form of logs, and 10.6 kg (20.6 lb) of purchased veneer, for a total wood need of 927 kg. These inputs yielded 470 kg (916 lb) of oven-dry plywood (wood only) and 98.4 kg (191.5 lb) of oven-dry hogged fuel that is about half bark. The 917 kg of wood in the logs had an accompanying 50.7 kg (99 lb) of oven-dry bark. See Table 3 for a listing of all PNW inputs and outputs. To produce 1.0 m^3 (or to produce 1.0 MSF) of SE plywood, it takes 1,070 kg (2,080 lb) of wood in the form of logs, and 9.50 kg (18.5 lb) of purchased veneer, for a total wood need of 1,075 kg. These inputs yielded 541 kg (1,055 lb) of oven-dry SE plywood, wood only, and 99.4 kg (194 lb) of oven-dry self-produced hogged fuel that is mostly bark. This weight of wood had 63.6 kg (124 lb) of oven-dry bark. See Table 4 for the listing of all SE plywood inputs and outputs. These tables also list the reported electric-

TABLE 3. *Gate-to-gate LCI inputs to produce a unit of plywood in the PNW.*[1]

	PNW plywood			
Inputs	SI unit	SI unit per m^3	Unit	Unit per MSF
Materials[2]				
Logs without bark	m^3	2.10E + 00	ft^3	6.56E + 01
	kg	9.17E + 02	lb	1.79E + 03
Phenol-formaldehyde resin	kg	8.15E + 00	lb	1.59E + 01
Extender and fillers[3]	kg	4.56E + 00	lb	8.90E + 00
Catalyst[3]	kg	5.69E − 01	lb	1.11E + 00
Soda ash[3]	kg	1.69E − 01	lb	3.30E − 01
Bark	kg	5.07E + 01	lb	9.90E + 01
Purchased				
Dry veneer	kg	3.28E + 00	lb	6.40E + 00
Green veneer	kg	7.28E + 00	lb	1.42E + 01
Electrical use				
Electricity	MJ	5.65E + 02	kWh	1.39E + 02
Fuel use				
Wood fuel (produced)[4]	kg	9.84E + 01	lb	1.92E + 02
Wood fuel (purchased)	kg	2.56E − 01	lb	5.00E − 01
Wood waste	kg	2.56E − 01	lb	5.00E − 01
Liquid petroleum gas	L	1.54E + 00	gal	3.59E − 01
Natural gas	m^3	5.22E + 00	ft^3	1.63E + 02
Diesel	L	1.69E + 00	gal	3.95E − 01
Water use				
Municipal water source	L	3.54E + 02	gal	8.28E + 01
Well-water source	L	1.26E + 02	gal	2.94E + 01
Recycled water source	L	1.28E + 00	gal	3.00E − 01

[1] Survey data for mill site collected in 2000.
[2] Materials and wood fuels are given on an oven-dry or solids weight basis.
[3] These materials were not included in the LCI analysis based on the 2% exclusion rule.
[4] Includes hogged bark and wood wastes produced within the system boundary; oven-dry weights.

ity, fuel, and water inputs for the production of each unit of plywood; these are unallocated values.

The data in Tables 3 and 4, along with the mills' emission data in Tables 5 (Franklin data only), 6, and 7 were the input data used in the SimaPro software to determine the life-cycle inventory of manufacturing a unit of plywood. The input logs (also referred to as round wood) were given on a volume basis and converted to weight. The resin used to produce plywood is a phenol-formaldehyde (PF) system that consists of the PF, water, extender and fillers, catalyst, and soda ash. The emissions data in these tables are unallocated (total) on-site emissions from the boilers fired with hogged fuel (wood and bark fuel) and natural gas (Table 5), from the veneer dryers that were heated with steam and/or direct-fired with natural gas and/or hogged fuel (Table 6), and from the hot presses (Table 7). The exclusionary rule of CORRIM's protocol states that if the contribution of a material by mass to the total is less than 2%, and it does not cause a significant environmental impact, the material can be excluded from the analysis. Therefore, the extender, fillers, catalyst, and soda ash were not included in the LCI analysis.

The emissions for the dryers are given in Table 6. The dryers are used to remove moisture from the wood veneers from about 25 to 100% moisture down to 3 to 6% moisture (oven-dry wood basis). Dryer temperatures are normally in the 150 to 185°C (300 to 365°F) range; however, the wood veneer does not experience this higher temperature until much of its moisture is evaporated near the output end of the dryer. Most emissions are generated at this time. One of the mills surveyed for the PNW had a direct-fired

TABLE 4. *Gate-to-gate LCI inputs to product a unit of plywood in the PNW.[1]*

Inputs	SE plywood			
	SI unit	SI unit per m^3	Unit	Unit per MSF
Materials[2]				
Logs without bark	m^3	2.11E + 00	ft^3	6.60E + 01
	kg	1.07E + 03	Lb	2.08E + 03
Phenol-formaldehyde	kg	1.01E + 01	Lb	1.97E + 01
Extender and fillers[3]	kg	6.46E + 00	Lb	1.26E + 01
Catalyst[3]	kg	7.18E − 01	Lb	1.40E + 00
Soda ash[3]	kg	8.10E − 01	Lb	1.58E + 00
Bark	kg	6.36E + 01	Lb	1.24E + 02
Purchased				
Dry veneer	kg	4.14E + 00	Lb	8.07E + 00
Green veneer	kg	5.33E + 00	Lb	1.04E + 01
Electrical use				
Electricity	MJ	4.96E + 02	kWh	1.22E + 02
Fuel use				
Wood fuel (produced)[4]	kg	9.94E + 01	Lb	1.94E + 02
Wood fuel (purchased)	kg	2.35E + 01	Lb	4.58E + 01
Wood waste	kg	3.11E + 01	Lb	6.07E + 01
Liquid petroleum gas	L	1.80E + 00	Gal	4.20E − 01
Natural gas	m^3	7.74E + 00	ft^3	2.42E + 02
Diesel	L	1.16E + 00	Gal	2.70E − 01
Water use				
Municipal water source	L	1.31E + 02	Gal	3.05E + 01
Well-water source	L	3.98E + 02	Gal	9.30E + 01
Recycled water source	L	3.51E + 00	Gal	8.20E − 01

[1] Survey data for mill site collected in 2000.
[2] Materials and wood fuels are given on an oven-dry or solids weight basis.
[3] These materials were not included in the LCI analysis based on the 2% exclusion rule.
[4] Includes hogged bark and wood wastes produced within the system boundary.

natural gas dryer, and because of this, the emissions report have components of CO, CO_2 (fossil), NO_X, and SO_2 that are not emitted from the steam-heated dryers. One mill in the PNW also used a fuel cell that combusted wood and bark hogged fuel which exhausted directly into the dryer, resulting in emissions charged to the dryer, thus the CO_2 biomass. The dryer emissions were used in the SimaPro modeling of LCI outputs. These data represent total emissions for dryers with no allocation or burdens assigned to the co-products. Assigning of burdens is done in the SimaPro software, and the impacts are given in the LCI outputs.

Emissions data were collected for the boilers and the veneer dryers, whereas emissions at the hot press were calculated from U.S. Environmental Protection Agency reports on plywood manufacturing (EPA 2001). The survey emissions data for the boiler are given in Table 5 along with comparative data contained in the Franklin Associates' database in SimaPro. All survey data, except for CO_2, were provided by the survey. The CO_2 data were calculated from EPA data on boiler emission (EPA 1999). In some cases a wood fuel cell was used for the combustion of hogged fuel or natural gas; because of a lack of data, the emissions were considered the same as for a boiler. The CORRIM survey boiler data are specifically for the PNW and SE regions, whereas the Franklin data are representative of wood-fired boiler operations throughout the U.S. The differences in the values can be attributed to the species differences of the fuel, the regional difference of the equipment used, and number of boilers sampled. For the SimaPro modeling of the plywood life-cycle inventory, the Franklin data were used for both the

TABLE 5. *Mill survey data on air emissions from wood fuel fired boilers compared to FAL[1] boiler data.*

	PNW		SE	
Air emission	Survey data kg/m³	FAL data kg/m³	Survey data kg/m³	Fal data kg/m³
Acetaldehyde	1.09E – 03	2.03E – 04	2.31E – 04	2.97E – 04
Acrolien	7.69E – 07	N/R[2]	2.08E – 05	N/R
CO	2.45E + 00	9.23E – 01	2.50E + 00	1.35E + 00
CO_2 (biomass)[3]	1.93E + 02	1.43E + 02	3.29E + 02	2.08E + 02
Formaldehyde	2.36E – 03	4.46E – 04	7.28E – 04	6.51E – 04
Methanol	N/R	N/R	2.65E – 03	N/R
NOx	4.15E – 01	1.05E – 01	5.48E – 01	1.58E – 01
Particulates	2.76E – 01	1.15E – 02	2.11E – 01	1.69E – 02
Particulates (PM10)	2.23E – 01	N/R	8.82E – 02	N/R
Phenol	1.49E – 04	2.71E – 03	3.47E – 06	3.96E – 03
SO_2	8.20E – 02	5.28E – 03	1.18E – 02	7.48E – 03
VOC	1.63E – 01	N/R	3.74E – 02	N/R

[1] Reference: SimaPro 5.0.009, PRe' Consultants 2001; Franklin Associates (FAL) 2001.
[2] N/R = not reported.
[3] The "survey" CO_2 was calculated from EPA Wood Waste Combustion in Boilers, AP-42, Section 1.6, EPA 1999.

TABLE 6. *Mill survey data on air emissions from drying veneer during the production of plywood.*

	PNW veneer dryers		SE veneer dryers	
Air emission[1]	kg/m³	lb/MSF	kg/m³	lb/MSF
Acetaldehyde	5.69E – 03	1.11E – 02	1.73E – 04	3.38E – 04
Acrolein	3.61E – 07	7.05E – 07	3.47E – 06	6.76E – 06
CO	7.69E – 02	1.50E – 01	6.25E – 02	1.22E – 01
CO_2 (biomass)[2]	5.02E + 00	9.80E + 00	0.00E + 00	0.00E + 00
CO_2 (fossil)	1.38E + 00	2.71E + 00	1.05E + 01	2.04E + 01
Formaldehyde	1.15E – 02	2.24E – 02	1.39E – 04	2.71E – 04
Methanol	1.76E – 02	3.44E – 02	3.70E – 04	7.21E – 04
NOx	2.56E – 02	4.99E – 02	2.08E – 02	4.06E – 02
Particulates	1.62E – 01	3.16E – 01	3.77E – 02	7.35E – 02
Particulates (PM10)	1.44E – 01	2.81E – 01	1.07E – 02	2.09E – 02
Phenol	1.41E – 03	2.76E – 03	1.61E – 04	3.15E – 04
SO_2	5.64E – 04	1.10E – 03	4.21E – 05	8.21E – 05
VOC	3.22E – 01	6.28E – 01	3.90E – 02	7.61E – 02

[1] Total air emissions as reported from surveys based on weighted production data.
[2] Biomass fuel consisting of bark and wood wastes; value calculated from EPA Plywood Manufacturing—Emission Factor Documentation, AP-42, Chapter 10, Table 10.5-2, 2001.

PNW and SE regions for the combustion of wood, natural gas, and propane.

Hot-pressing is done in the plywood process to provide intimate contact between veneers, while the PF adhesive cures as a result of temperature in the 163 to 171°C (325 to 340°F) range. Emissions are generated from the wood as a result of the high temperatures and the resin off-gassing during cure. Calculated emissions from the hot press are given in Table 7. There are no fuel combustion emissions since steam is used to heat the metal platens of the hot press; the emissions to generate the steam are accounted for at the boiler.

A detailed breakdown of the energy use and emissions associated with the production of the phenol-formaldehyde resin can be found in Wilson and Sakimoto (2004).

MANUFACTURING ENERGY

Energy for the production of plywood comes in the form of electricity, diesel, liquid pretroleum gas (LPG), wood and bark hogged fuel,

TABLE 7. *Total air emissions for hot-pressing softwood plywood during production (EPA 2001).*

Air emission[1]	PNW hot presses		SE hot presses	
	kg/m^3	lb/MSF	kg/m^3	lb/MSF
Acetaldehyde	2.15E – 03	4.19E – 03	2.15E – 03	4.20E – 03
Formaldehyde	9.74E – 04	1.90E – 03	9.74E – 04	1.90E – 03
Methanol	7.13E – 02	1.39E – 01	7.18E – 02	1.40E – 01
Particulates	6.15E – 02	1.20E – 01	9.12E – 02	1.78E – 01
Phenol	7.13E – 04	1.39E – 03	7.18E – 04	1.40E – 03
VOC	1.28E – 01	2.49E – 01	1.28E – 01	2.50E – 01

[1] Calculated from EPA Plywood Manufacturing, Emission Factor Documentation, AP-42, Chapter 10, Table 10.5-6, 2001.

and steam. The electricity is used to operate the debarker, bucker, lathe, pneumatic and mechanical conveying equipment, fans, hydraulic pumps, saws, and a radio-frequency redryer (one mill only). Electricity was used in all unit processes. Diesel fuel use is attributed solely to log loaders in the debarking unit process. As such, all of the diesel use was assigned to this process. Forklift trucks used small amounts of LPG in one or more of the remaining five unit processes. This fuel use was assigned evenly over the five unit processes from conditioning of logs through to the trimming and sawing of panels; as such, 20% of the LPG use was assigned to each of these operations.

The source of fuel used to generate the electricity used in the manufacturing process is very important in determining the type and amount of impact in the life-cycle inventory (LCI) and life-cycle assessment (LCA). The breakdown of electricity by fuel source for the PNW and SE regions is given in Table 8. The source of this data is the U.S. Department of Energy (USDOE 2001). In 2000 the dominant form of electricity generation in the PNW region was hydro representing 74.3% of the total, followed by natural gas at 12.3% and coal at 8.1%. In the SimaPro impact analysis using the Franklin database, no impacts are associated with hydro-generated electricity, ignoring the impact on fisheries and other natural issues. However, SimaPro does consider the impact values associated with the combusting of coal and natural gas, and use of uranium. For the SE region, the average fuel source breakdown is coal at 45.6%, natural gas at 23.0%, nuclear at 21.6%, and lesser contributions from petroleum at 4.5%, hydroelectric at 1.8%, and the remaining sources at 3.5%. For a fuel source breakdown by state for each region, see Wilson and Sakimoto (2004).

TABLE 8. *Breakdown of generation of electricity by primary energy sources as defined by the U.S. Department of Energy (USDOE 2001).*

Fuel source	Percentage share, 2000	
	PNW	SE
Coal	8.1	45.6
Petroleum	0.3	4.5
Natural gas	12.3	23.0
Nuclear	4.0	21.6
Hydro	74.3	1.8
Others	1.1	3.5
Total	100	100

All of the bark generated as a result of debarking logs, as well as some wood residues in the mill, and some purchased wood residues were combined to make wood and bark hogged fuel (also referred to as biomass fuel) for combusting in boilers and fuel cells. For energy calculations, the higher heating value (HHV) of a fuel was used. Table 9 gives the on-site fuel energy for both unallocated and allocated to the plywood. For both cases, the amount of wood fuel (biomass fuel) used is 88% and 90% of the total fuel use for the PNW and SE regions, respectively. This is significant in that a large amount of the mills' fuel needs to produce heat is generated on site as wood and bark hogged fuel during processing. In terms of total energy needs on-site, which includes electricity use, the hogged fuel represents 72% and 79% for the PNW and SE, respectively. The allocated on-site energy use is about 64% of the total unallocated

TABLE 9. *Fuel and electricity energy[1] use at the mill site; both unallocated and allocated to plywood on a mass basis.*

	Unallocated energy use at mill				Allocated energy use at mill			
	PNW on-site energy		SE on-site energy		PNW on-site energy		SE on-site energy	
	MJ/m^3	Btu/MSF	MJ/m^3	Btu/MSF	MJ/m^3	Btu/MSF	MJ/m^3	Btu/MSF
Renewable fuel use								
Wood fuel (biomass)	2.25E + 03	1.89E + 06	3.22E + 03	2.07E + 06	1.40E + 03	1.18E + 03	1.99E + 03	1.67E + 06
Non-renewable fuel use								
Liquid petroleum gas	4.09E + 01	3.43E + 04	4.78E + 01	4.01E + 04	2.02E + 01	1.70E + 04	3.51E + 01	2.95E + 04
Natural gas	2.00E + 02	1.68E + 05	2.97E + 02	2.49E + 05	1.50E + 02	1.26E + 05	2.77E + 02	2.32E + 05
Diesel	6.54E + 01	5.49E + 04	4.47E + 01	3.75E + 04	3.40E + 01	2.85E + 04	2.29E + 01	1.92E + 04
Electricity use								
Electricity	5.65E + 02	4.74E + 05	4.96E + 02	4.16E + 05	3.81E + 02	3.20E + 05	3.86E + 02	3.24E + 05
Total	3.12E + 03	2.62E + 06	4.11E + 03	3.45E + 06	1.99E + 03	1.67E + 06	2.71E + 03	2.27E + 06

[1] Energy values were determined for the fuels using their higher heating values (HHV) in units of MJ/kg as follows: liquid petroleum gas 54.0, natural gas 54.4, diesel 44.0, and wood oven-dry 20.9. Electricity was calculated at 3.6 MJ/kWh.

on-site use. Table 10 gives the fuel energy for the allocated cumulative energy. The cumulative energy considers the on-site, as well as the off-site energy such as the energy to produce and deliver resin, electricity, natural gas, LPG, and gasoline, and includes the energy value of feedstock to make resin. For the allocated cumulative energy, of the total energy use, the wood fuel represents 49% and 45% for the PNW and SE, respectively. Wood fuel (biomass) represents a significant portion of energy needs. The biomass fuel offers significant advantages when it comes to sustainability, and reducing the impact of fuel combustion on global warming.

LIFE-CYCLE INVENTORY

Two life-cycle inventory scenarios were used to provide the emissions generated to air, water and land for both the PNW and SE regions, Tables 11 and 12, respectively. The values are allocated emissions for plywood based on its mass contribution at each unit process. The SimaPro models developed for the unit processing of plywood would need to be used to calculate the allocated emissions assigned to each coproduct.

The first scenario is a classical LCI that considers the cumulative on-site and off-site impacts due to plywood production, the emissions to manufacture and deliver electricity and all fuels except the wood and bark hogged fuel, and the production of resin. This scenario does not include the impacts for production and delivery of logs, and the delivery of resin and purchased veneer. To obtain a complete listing of these allocated LCI emissions, see Wilson and Sakimoto (2004). For a cradle-to-gate listing of emissions, which would include all impacts from forest to the exit gate of the plywood mill, see Puettmann and Wilson (2005). The second scenario considers only the mill site allocated impacts for emissions from combustion and processing of wood. Biomass CO_2 and fossil CO_2 are accounted separately since biomass CO_2 is considered to have a neutral impact on the global warming, whereas the fossil fuel CO_2 contributes significantly to global warming. Biomass

TABLE 10. *Fuel and electricity energy[1] cumulative use considering both site and off-site energies allocated to plywood on a mass basis.*

	Allocated cumulative energy use			
	PNW energy		SE on-site energy	
	MJ/m^3	Btu/MSF	MJ/m^3	Btu/MSF
Renewable fuel use				
Wood fuel (biomass)	1.55E + 03	1.30E + 06	2.29E + 03	1.92E + 06
Non-renewable fuel use				
Coal	1.30E + 02	1.09E + 05	7.39E + 02	6.20E + 05
Crude oil	2.69E + 02	2.26E + 05	4.58E + 02	3.84E + 05
Natural gas	8.76E + 02	7.35E + 05	1.49E + 03	1.25E + 04
Uranium	9.83E + 00	8.25E + 03	5.46E + 01	4.58E + 04
Electricity				
Energy from hydro power	3.07E + 02	2.58E + 05	7.92E + 00	6.65E + 03
Energy from other sources	4.56E + 00	3.82E + 03	1.53E + 01	1.28E + 04
Total	3.14E + 03	2.64E + 06	5.06E + 03	4.24E + 06

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

CO_2 is considered impact-neutral because the CO_2 can be taken in by trees during their growing process, using the carbon to generate wood tissue, and releasing oxygen to the atmosphere (EPA 1999). For plywood produced in the PNW, CO_2 generated as a result of biomass combustion is 79% of the cumulative CO_2 emissions and 96% of CO_2 produced at the site. For plywood produced in the SE, CO_2 biomass is 67% of the cumulative CO_2 and 98% of the site CO_2. Another advantage of the use of biomass for fuel is that it is generated within the manufacturing operation and is considered renewable.

CARBON BALANCE

The element carbon was tracked gate-to-gate for the manufacture of softwood plywood. Only carbon in wood and bark was tracked, because it represents CO_2 removed from the atmosphere that does not contribute to global warming. The only challenge in tracking the carbon occurred in air emissions. Whereas some emissions such as CO_2 fossil were easy to discern whether they were due to wood related emissions, there were other emissions that could not easily be categorized by its sources. This analysis followed carbon flow from inputs of logs, bark, and purchased veneer, to outputs of product, co-product, and emissions. The percentage of carbon in wood was taken from a separate study done by Birdsey (1992). Carbon content of wood products is also available in Skog and Nicholson (1998). The percentage of carbon was a weighted average of the wood species used to produce the plywood in each region. Carbon percentages for materials other than wood were calculated using atomic masses of each element from their chemical formula.

Table 13 describes the flow of carbon that is wood-based (also referred to as biogenic carbon flow) from the input to the output. Values are based on the mass balance of wood and bark into and out of the mill and on the LCI of unallocated emissions at the mill site. The biogenic carbon balance of input to output has a difference of only a couple percent, with 1% more for the PNW and 7% less output for the SE. To produce 1.0 m^3 of PNW plywood, for the carbon flow it takes an input of 504 kg of carbon in wood and bark for an output of 241 kg in plywood, 198 kg in co-products, and 59 kg in emissions to air and land. For 1.0 m^3 of SE plywood, it takes an input of 983 kg of carbon in wood and bark to produce an output of 290 kg in plywood, 288 kg in co-products, and 94 kg in emissions to air and land.

The co-products will go to other manufacturing operations to be made into other wood prod-

TABLE 11. *Life-cycle inventory results for production of plywood in the PNW region, gives both allocated site and cumulative emissions to air, water, and land.*

Substance	Allocated cumulative		Allocated site	
	kg/m^3	lb/MSF	kg/m^3	lb/MSF
Emissions to air				
Acetaldehyde	6.10E − 03	1.19E − 02	6.10E − 03	1.19E − 02
Acrolein	4.49E − 07	8.75E − 07	2.71E − 07	5.28E − 07
CO	1.07E + 00	2.08E + 00	9.94E − 01	1.94E + 00
CO_2 (biomass)	1.46E + 02	2.85E + 02	1.46E + 02	2.85E + 02
CO_2 (fossil)	3.99E + 01	7.78E + 01	6.15E + 00	1.20E + 01
Formaldehyde	1.92E − 02	3.74E − 02	1.06E − 02	2.06E + 02
Methane	1.09E − 01	2.13E − 01	3.65E − 05	7.13E − 05
Methanol	6.97E − 02	1.36E − 01	6.97E − 02	1.36E − 01
NOx	3.33E − 01	6.50E − 01	1.94E − 01	3.79E − 01
Particulates	1.95E − 01	3.81E − 01	1.92E − 01	3.75E − 01
Particulates (PM10)	1.16E − 01	2.27E − 01	1.14E − 01	2.22E − 01
Particulates (unspecified)	1.29E − 02	2.52E − 02	—	—
Phenol	1.55E − 02	3.02E − 02	4.33E − 03	8.44E − 03
SOx	5.43E − 01	1.06E + 00	9.23E − 03	1.80E − 02
VOC	3.43E − 01	6.69E − 01	3.43E − 01	6.69E − 01
Emissions to water				
BOD	7.38E − 04	1.44E − 03	2.92E − 06	5.69E − 06
C1−	3.20E − 02	6.24E − 02	—	—
COD	8.56E − 03	1.67E − 02	2.50E − 04	4.88E − 04
Dissolved solids	7.07E − 01	1.38E + 00	4.90E − 04	9.56E − 04
Oil	1.26E − 02	2.45E − 02	—	—
Suspended solids	1.68E − 02	3.27E − 02	5.23E − 04	1.02E − 03
Emissions to land				
Solid waste	9.46E + 00	1.88E + 01	6.10E + 00	1.19E + 01

ucts such as paper, particleboard, and medium density fiberboard where their carbon will continued to be stored. It is significant to track this stored carbon in products and co-products since for every 1.0 kg of carbon in wood products, it represents 3.67 kg of CO_2 removed from the atmosphere.

CONCLUSIONS

A study was conducted of the life-cycle inventory of the manufacture of softwood plywood. To collect production data of all inputs and outputs from the mills, surveys were conducted of five mills in each of the two major production regions of the U.S., the Pacific Northwest and Southeast. The production of these mills represented 26% and 14% of total production for PNW and SE regions, respectively. The data were found to be of high quality based on comparisons of data between mills and regions, and upon mass and energy balances. Input data consisted of fuels, electricity, logs, veneer, and resin, while outputs consisted of plywood product, a variety of wood co-products sold to other operations, and emissions to air, water, and land.

The cumulative boundary system looked at the environmental impacts of manufacturing plywood from the log delivered to the mill through production of plywood. The LCI data for plywood are presented on a production unit of 1.0 m^3 and 1.0 MSF (3/8-inch basis), the U.S. industry product unit. The impact considered those impacts including the production and delivery of electricity and fuel, and the production of resin. Transportation distances of materials to the mill are given. To obtain a complete cradle-to-gate LCI analysis for softwood plywood, the LCI data for logs, and the transportation of logs,

TABLE 12. *Life-cycle inventory results for production of plywood in the SE region, gives both allocated site and cumulative emissions to air, water, and land.*

Substance	Allocated cumulative kg/m³	Allocated cumulative lb/MSF	Allocated site kg/m³	Allocated site lb/MSF
Emissions to air				
Acetaldehyde	2.36E − 03	4.61E − 03	2.36E − 03	4.61E − 03
Acrolein	4.04E − 06	7.88E − 06	—	—
CO	1.61E + 00	3.14E + 00	1.47E + 00	2.87E + 00
CO_2 (biomass)	2.17E + 02	4.24E + 02	2.17E + 02	4.24E + 02
CO_2 (fossil)	1.06E + 02	2.07E + 02	5.18E + 00	1.01E + 01
Formaldehyde	1.41E − 02	2.76E − 02	2.14E − 03	4.17E + 03
Methane	2.53E − 01	4.93E − 01	4.87E − 05	9.50E − 05
Methanol	6.36E − 02	1.24E − 01	6.36E − 02	1.243 − 01
NOx	7.84E − 01	1.53E + 00	2.10E − 01	4.09E − 01
Particulates	2.92E − 01	5.17E − 01	2.89E − 01	5.64E − 01
Particulates (PM10)	6.82E − 02	1.33E − 01	5.38E − 02	1.05E − 01
Particulates (unspecified)	6.82E − 02	1.33E − 01	—	—
Phenol	2.04E − 02	3.98E − 02	4.90E − 03	9.56E − 03
SOx	1.10E + 00	2.15E + 00	1.10E − 02	2.15E − 02
VOC	1.48E − 01	2.88E − 01	1.48E − 01	2.88E − 01
Emissions to water				
BOD	1.07E − 03	2.09E − 03	3.91E − 06	7.63E − 06
C1−	4.77E − 02	9.31E − 02	—	—
COD	1.05E − 02	2.04E − 02	3.33E − 04	6.50E − 04
Dissolved solids	1.04E + 00	2.03E + 00	6.56E − 04	1.25E − 03
Oil	1.86E − 02	3.63E − 02	—	—
Suspended solids	5.03E − 02	9.81E − 02	6.97E − 04	1.36E − 03
Emissions to land				
Solid waste	2.33E + 01	4.54E + 01	9.33E + 00	1.82E + 01

TABLE 13. *Biogenic carbon balance, tracking flow of wood and bark carbon through the plywood manufacturing process.*

Substance	Carbon content PNW kg/m³	PNW lb/MSF	SE kg/m³	SE lb/MSF
Input				
Wood materials[1]	504	983	625	1220
Output				
Plywood	241	470	290	566
Co-products	198	387	288	561
Air emissions	55	107	87	170
Solid emissions	4	8	7	13
Total	498	972	671	1310

[1] Includes wood and bark materials.

veneer, wood fuel (biomass) and resin based on recorded mileage would have to be added to the gate-to-gate LCI data provided in this study.

Energy use for manufacturing plywood is dominated by the combustion of wood fuel (biomass), which is comprised of wood and bark waste generated during the manufacture of plywood. Wood fuel for the PNW and SE regions, respectively, represented 72% and 79% of the mill site use of fuel and electricity energy, and 49% and 45% of the cumulative energy use, which included fuel to produce and transport electricity, fuels, and resin, and the feedstock to produce resin. Wood fuel contributes 96% and 98% of CO_2 produced at the site for the PNW and SE respectively, and 79% and 67% of the CO_2 produced cumulatively due to the combustion of fuels. This is beneficial in that the wood-derived CO_2 is considered to have a neutral impact on global warming and greenhouse gases in that it can be up taken by the forest ecosystem, storing carbon in the wood and releasing oxygen to the atmosphere. Combustion of fossil fuels, unlike that for biomass, generates CO_2 that contributes to both global warming and greenhouse gases. Energy to produce the electricity varied significantly between the two regions, with the PNW heavily dependent upon hydro generation, while the SE was dependent upon coal, oil, and uranium fuels. Resins used to bond the veneers together to produce plywood were also dependent upon fossil fuels for both energy and feedstock.

Carbon studies were conducted to track carbon from the input materials through processing to produce plywood, co-products, and emissions. Only carbon related to wood and bark was tracked since this carbon represents CO_2 removed from the atmosphere during the growing of trees. Wood-based materials are about 50% carbon, whether it is in a product such as plywood or a co-product such as peeler cores, sawdust, and plywood trim that eventually are converted into other wood products for the consumer.

The LCI data for softwood plywood are made available for public access through this publication and the U.S. LCI Database, which is a database for all major materials and manufacturing processes in the U.S.

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