LIFE-CYCLE INVENTORY OF PARTICLEBOARD IN TERMS OF RESOURCES, EMISSIONS, ENERGY AND CARBON

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Abstract. Life-cycle inventory (LCI) data are needed to scientifically document the environmental performance of materials for applications as governed by the many new green building standards, purchasing guidelines, and energy and climate change policy issues. This study develops the LCI data for particleboard, a composite wood panel product comprised of wood particles, urea–formaldehyde resin, wax, and other additives. Data are given for both gate-to-gate (particleboard manufacture) and cradle-to-gate (from the product upstream to in-ground resources) that, in addition to gate-to-gate impacts, include those to produce and deliver input fuels, electricity, water, wood residue, resin, wax, catalyst, and scavenger. LCI output data are given per 1.0 m^3 of particleboard in terms of raw materials use and emissions to air, water, and land. Data are also presented on embodied energy, carbon flux, store, and footprint. Particleboard has favorable characteristics in terms of energy use and carbon store. Of significance for the LCI of particleboard is the large component of embodied energy because of the use of wood fuel, a renewable resource, and its small carbon footprint, which lessens its impact on climate change.

Keywords: Environmental performance, particleboard, wood products, life-cycle inventory, LCI, CORRIM, embodied energy, carbon store, carbon footprint.

INTRODUCTION

The objective of this study was to develop the life-cycle inventory (LCI) data for particleboard, a composite wood panel product, as produced in the US. In 2004, the US particleboard industry produced 7,618,167 m^3 (CPA 2005).[1]

Particleboard is produced from industrial wood residues such as shavings, sawdust, plywood trim, fines, and chips and can be produced from log and urban wood waste chips. Generally, production facilities are located in regions of the US that are producers of primary wood products such as lumber and plywood to draw on their coproduct wood residue resources. Particleboard falls into two product categories, mostly into industrial as substrate (96%) for making household and office furniture, kitchen and bath cabinets, store fixtures, and door components, and a small portion into flooring (4%) as underlayment.

An LCI consists of an accounting of all inputs and outputs of a material from its natural resources in the ground through production of a product and can include downstream transportation, product use, disposal, and/or recycling. LCI data are invaluable when it comes to establishing whether a product is green in terms of its favorable environmental performance, as a benchmark for improving environmental performance, and for comparison with alternative materials. The data form the foundation for the scientific assessment in terms of a variety of environmental performance measures. It provides data that can be used to establish the performance of particleboard for many green-type product standards, guidelines,

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[1] Production of panels in the US is traditionally measured on a 1000 square foot (MSF) 3/4-in.-thickness basis and is now also given in SI units as m^3 with a MSF equivalent to 1.7698 m^3.

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and public policies. Issues in which the data can be used are sustainability, global warming, climate change, carbon storage, carbon trading and caps, biofuel use, green-product purchasing, and green building.

Particleboard is a nonstructural panel product developed in the 1950s to use industrial wood residue from the production of primary wood products like lumber and plywood. These wood residues were previously burned or sent to a landfill for disposal as waste material. Over the years, the product has evolved into a highly engineered product designed to meet specific end-use requirements. Particleboard is produced from industrial wood residues that are refined to small particles that are dried, blended with resin and wax, formed into a mat that is consolidated and cured under pressure and heat, sawn to dimension, and sanded to thickness. Particleboard is produced to densities ranging from about 600 – 800 kg/m^3 and to material properties listed in the American National Standard ANSI A208.1-2009 (ANSI 2009). The panels are produced in thicknesses ranging from 9 – 32 mm and in widths from 1.22 – 1.52 m and lengths from 2.44 – 7.32 m.

PROCEDURE

LCI of manufacturing particleboard for this study covers the environmental impacts from the in-ground resources for wood, resin, catalyst, wax, fuels, and electricity through transportation and manufacture of the particleboard. This is referred to as a cradle-to-product gate study (Fig 1). The study was conducted for the 2004 production year and done in accordance with the Consortium for Research on Renewable Industrial Materials (CORRIM) guidelines (CORRIM 2001) and ISO 14040 and 14044 protocol (ISO 2006a, ISO 2006b). Primary data were collected by survey for transportation of materials to the mill and production of the particleboard. Secondary data were used for resources, extraction, and processing of resources, whereas all forest, wood residue, and resin data were from earlier CORRIM primary data sets.

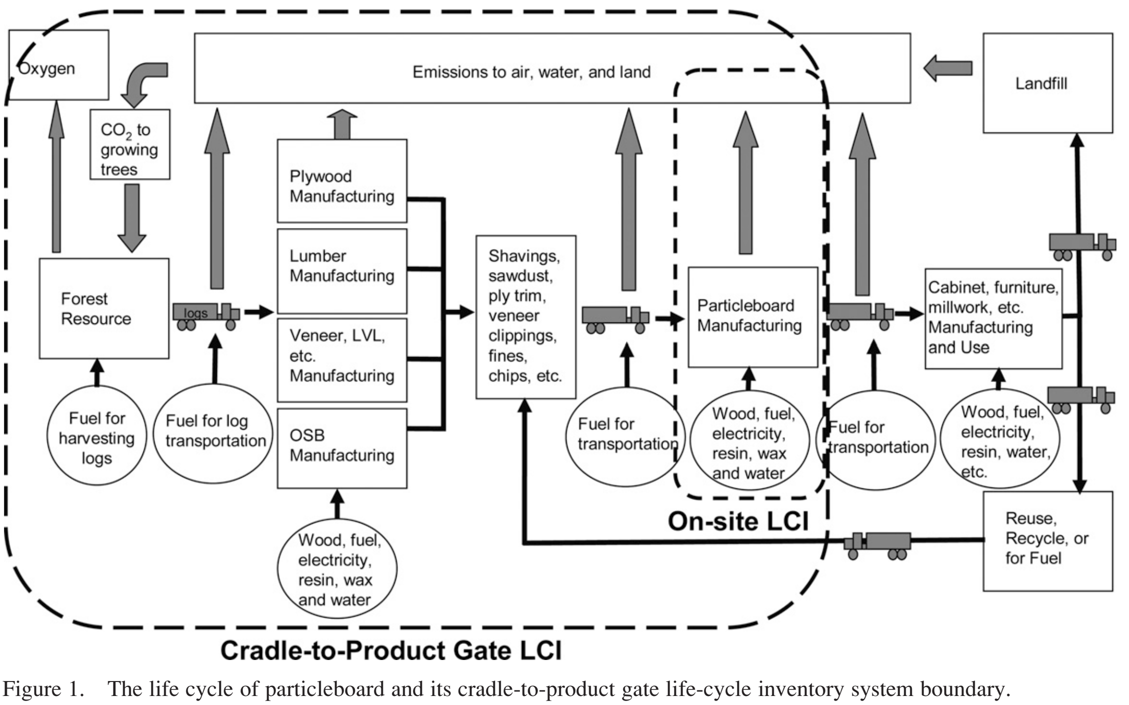

Figure 1. The life cycle of particleboard and its cradle-to-product gate life-cycle inventory system boundary.

The particleboard manufacturing data were collected by direct survey questionnaire of the industry documenting all inputs of materials, fuels, and electricity and all outputs of product, coproduct, and emissions to air, water, and land. For a copy of the survey form, see Wilson (2008). The five mills surveyed were selected to be representative of US production practices; they produced 1,738,448 m^3 in 2004, representing 23% of total US production. The LCI data for the input wood residues were from data and analyses done in earlier CORRIM studies for the production of residues as coproducts from softwood plywood and lumber manufacture (Milota et al 2005; Wilson and Sakimoto 2005). Also included from earlier CORRIM studies were the LCI of the forest resources, harvesting, and transportation impacts (Johnson et al 2005) and the LCI of urea–formaldehyde (UF) resin (Wilson 2009, 2010) used to bond the particleboard during its manufacture. Secondary data were obtained for impacts associated with the manufacture, delivery, and consumption of electricity and all fuels for the US (FAL 2004; PRé Consultants 2007; USDOE 2007). LCI data for wax, catalyst, and urea scavenger and their input chemicals (Ecoinvent 2004) were adjusted to US fuel, electricity, and transportation values using the FAL database where appropriate.

Survey Data Analysis

The survey data were analyzed for quality by assessing for outliers and conducting mass and energy balances. The data for all wood inputs and outputs are given as oven-dry, whereas chemical inputs of resin, wax, catalyst and scavenger are given as 100% solids. The data for each mill were converted to a unit of production basis, in this case, one cubic meter (1.0 m^3). Any data outliers were resolved by contacting mill personnel. Mass balance considering all inputs of materials—wood, resin, wax, catalyst, and scavenger—and all outputs of product, coproduct, and emissions had a difference of 4.8%, which is within the CORRIM protocol acceptable value of 5%. Energy balances were done to determine the expected energy use to dry the desired amount of water from the wood residues during processing. The average MC of wood material incoming to the mill was 25.7% on an oven-dry weight basis and the target MC for the dried material was 3 – 5%. Considering the energy content of the fuels and the amount of moisture removed, the energy use per 1.0 kg of water removed was 7.81 MJ based on the fuels' higher heating value (HHV). The energy use was found to be as expected. The data for the mills were then weight-averaged based on the production of each mill and the total production; only the weight-averaged data are presented. The weight-averaged mill produced 347,690 m^3 of particleboard annually with an average density of 746 kg/m^3.

Manufacturing Process

The particleboard manufacturing process is highly automated, process–controlled, and fairly linear (Fig 2). The process consists of the following production steps.

Sort and store. Wood residue is delivered to the mill normally by truck; the residue consists of shavings, sawdust, plywood trim, fines, and chips of various moisture contents; the residue is sorted by geometry and MC and stored under cover; its MC can range from 10 – 100% on an oven-dry weight basis.

Screening. Wood residue is passed through a set of screens that sort particles by size. The oversized particles are then refined with desired-sized particles for use in face and core layers and undersized particles, referred to as fines, either put into the board, the most common practice, or sometimes used as fuel for dryers.

Refining. Oversized particles are then refined, a process of mechanically reducing the particle geometry into uniform sizes of desired dimensions; this process is usually accomplished with the use of refiners, hammermills, and occasionally flakers and hogs. Particulate emissions are addressed by baghouses and cyclones.

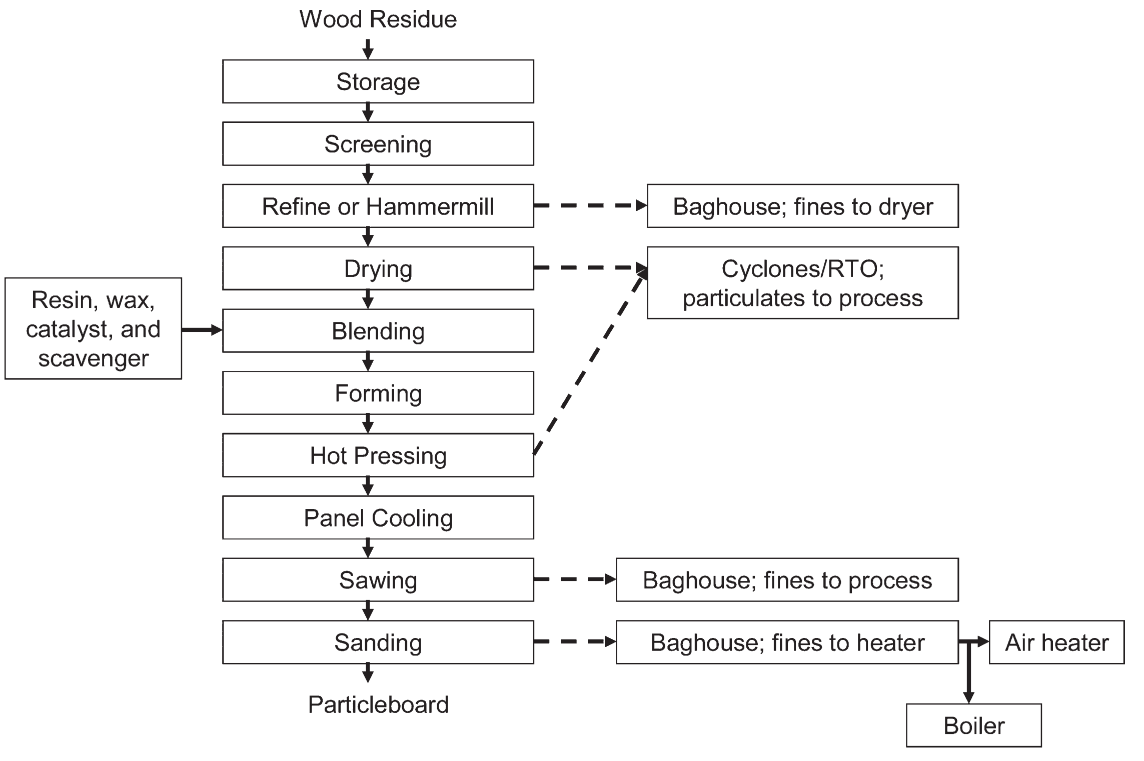

Figure 2. On-site process flow for the production of particleboard.

Drying. Particles are sent through dryers, normally rotary dryers of either single-pass or triple-pass configuration. Particles enter the dryers at moisture contents of 10 – 100% oven-dry wood basis and are dried to a targeted MC of about 3 – 5% depending on whether the particles will be used for face or core layers. The dryers are normally direct-fired with natural gas, although some dryers also use sander dust from a later process step. When wood dries at elevated temperatures in the dryers, air emissions consisting of particulates and volatile organic compounds (VOCs) are released. Emissions from dryers go to cyclones and control devices such as regenerative thermal oxidizers (RTOs), regenerative catalytic oxidizers (RCOs), and biofilters.

Blending. This is a process in which resin, wax, catalyst, and scavengers are distributed in the form of discrete droplets onto the wood particles. The resin most used is UF; however, some products are made with either melamine urea formaldehyde or polymeric isocyanate resins for those products in which greater moisture resistance is desired.

Forming. Blended particles are distributed into a flat mat in usually multiple layers of three or five consisting of face and core layers—the size of particles, their moisture and resin content are controlled for the face and core layers to obtain desire panel properties.

Hot pressing. Formed mats are conveyed into large multiopening presses in which all openings close simultaneously. The presses operate at sufficient temperature (about 170°C), pressure (about 5.2 MPa), and duration to cure the resin. The physical properties of the panel are controlled during pressing. As a result of the elevated temperature and resin curing, particulates and air emissions of VOCs, hazardous air pollutants (HAPs), and other related emissions are generated. Emissions, if treated, go to control devices such as RTOs, RCOs, and biofilters.

Cooling. Hot panels exiting the press are placed on a cooling wheel to enable the temperature of the panels to drop below a value at which UF resin could start to break down with time and emit formaldehyde gas. Limited amounts of air emissions occur at this point.

Sanding. Panels are sanded on both major surfaces to targeted thickness and smoothness. Sander dust coming off this process can either be recycled back into the process before the forming or it is used as fuel for the dryers. Particulate emissions are addressed by baghouses and cyclones.

Sawing. Relatively large panels are sawn to dimensions of panel width and length. Panel trim is hammermilled into particles and sent back with the saw dust into the process before the former. Particulate emissions are addressed by baghouses and cyclones.

The panels are then stacked and prepared for shipping. Other important processes are the boiler and oil heater and their combustion of fuel to generate processing heat and emission control devices such as baghouses, cyclones, biofilters, RTOs, and RCOs. The boilers are generally fired with wood residue, natural gas, or oil fuels; with this combustion, air emissions of CO_2, CO, and others are generated. The emission control devices are used to reduce particulate and chemical emissions. Of significance is the large quantity of natural gas and electricity used to operate the RTO and RCO systems and similarly large quantities of electricity to operate biofilter systems. Three of the five mills used a combination of cyclones, baghouses, and RTOs to reduce particulates, VOC, and HAP emission levels. Implementation of the new Plywood and Composite Wood Products Maximum Achievable Control Technology (PCWP MACT) rule necessitates that all particleboard mills that cannot meet its emissions averaging, work practice standards, or production-based limit must have some type of emission control system installed to meet regulations (USEPA 2004). Therefore, the other two mills will have likely installed HAP control systems resulting in a lowering of the average HAP emissions below those stated in this study and in turn increasing emissions related to the use of natural gas and/or electricity for their operation.

Functional Unit

For this study, material flows, fuel and electricity use, and emissions data are normalized to a per-production unit volume basis of 1.0 m^3—the functional unit—of finished particleboard ready to ship. For those LCI practitioners that conduct studies on a mass basis, 1.0 m^3 of particleboard weighs 746 kg oven dry; therefore, by dividing the data in this study by its weight will give all flows, materials, and emissions on a per 1.0 kg basis.

Life-Cycle Inventory Modeling

The environmental impact analysis was done using SimaPro 7.1 software and included the Franklin Associates (FAL) database to provide impacts for fuels and electricity for the US (PRé Consultants 2007). For materials not covered in the FAL database, the Ecoinvent v1.0 database (Ecoinvent 2004), a comprehensive database for Europe, was used to determine environmental impacts; however, its data were adjusted to US fuels, electricity, and transportation using FAL processes. Two boundary systems were modeled: 1) the on-site for particleboard manufacture only, also referred to as gate-to-gate; and 2) the cradle-to-product gate to encompass all upstream impacts from the product mill exit to include all material uses back to their in-ground resources. Mass-based allocation was used for all input and output resources and impacts.

System Boundary Conditions

A black-box approach was selected for modeling the LCI of the particleboard production process. Whereas unit process approaches were used in earlier CORRIM studies of lumber and plywood production (Milota et al 2005; Wilson and Sakimoto 2005), it is not needed in this case because unlike those processes that have a higher percentage of coproduct that are generated at various steps throughout the process, particleboard production has little if any coproduct. Furthermore, it is a complex process of separating the process into unit processes because of the lack of emissions data for each unit process and their flow in and out of the emission control units. In a black-box approach for the on-site system boundary, all inputs flow into the box, and all outputs flow out of the box (Fig 3). For on-site emissions only, those emissions that occur because of on-site combustion of fuels whether for process heat or operating equipment and those as a result of processing the wood are considered. For the cradle-to-product gate emissions, all impacts are considered, including those for the manufacture and delivery of wood residues, fuels, electricity, wax, catalyst, and scavenger; this is modeled using the various processing steps. The cradle-to-product gate system boundary covers the environmental impacts from the forest and raw resources in-ground through all product and coproduct processing steps. Only a small amount of coproduct was produced—0.7%—as wood fuel sold to other manufacturers.

Materials Flow

Those materials considered in the LCI analysis included input materials of wood residues, UF resin, wax emulsion, ammonium–sulfate catalyst, and urea scavenger. Other resins were used for making moisture-resistant panels; however, because of their small percentage of use, they were not considered in this study. The other resins included melamine urea formaldehyde and polymeric isocyanate.

LCI data of this study are only for UF-bonded particleboard, which represents 98% of panels produced in the survey. Although the nonwood inputs are given on a 100% solids weight, they were used in manufacturing as neat (with water) at their average percentage of solids as follows: UF resin 65%, wax 53%, ammonium–sulfate catalyst 30%, and urea scavenger 40%. The urea scavenger is used to capture excess formaldehyde to prevent its emission from the panel.

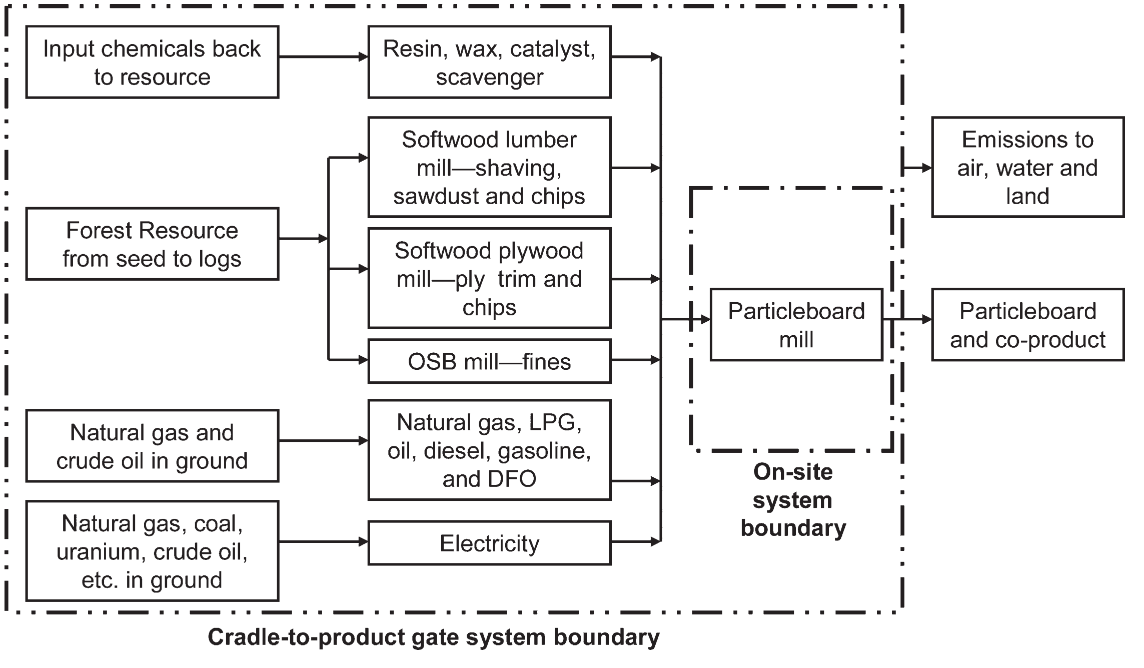

Figure 3. System boundaries for both on-site and cradle-to-product gate impact analyses.

Other catalyst and scavenger chemicals can be used, but these are representative of practice. The wood residue is representative of the wood species used to produce lumber and plywood in the major production centers of the US, which includes softwoods for the southeast and Pacific Northwest regions. The input MC on an oven-dry weight basis for each type of wood residue was as follows: green hog chips 42%, dry hog chips 18%, green shavings 35%, dry shavings 15%, green sawdust 71%, plywood trim 8%, and oriented strandboard (OSB) fines 8%.

Each 1.0 m^3 of finished particleboard has an oven-dry weight of 746 kg consisting primarily of wood residue of 672 kg (90%) and resin of 68 kg (9.2%) of the total board weight. Lesser amounts of wax at 2.5 kg (0.3%), catalyst at 0.72 kg (0.1%), and urea scavenger at 2.9 kg (0.4%) make up the remainder of the board's weight.

Transportation

The delivery of materials to the mills is by truck, although some resin is delivered by pipeline from adjacent resin plants. Table 1 gives the one-way delivery distances for the material inputs. Usually these deliveries have no back haul of other materials.

Assumptions

Specifics on all conditions and assumptions for this LCI study are given in a CORRIM report by Wilson (2008).

Particleboard Manufacture

Table 2 provides a listing of all inputs and outputs for the on-site manufacture of particleboard. These inputs yielded 1.0 m^3 of particleboard weighing 746 kg comprised of wood, resin, wax, catalyst, and scavenger. The input of industrial wood residue of 672 kg was produced as a coproduct in the manufacture of lumber, plywood, and other primary wood products. The input wood residue was used for particleboard and also provided wood for process fuel and wood sold as fuel. Of the wood fuel generated internally in the manufacturing process, 25 kg of sander dust was burned in the particle dryers and 2.1 kg of wood residue was burned in either the boiler or dryer. A small amount of coproduct was produced as wood residue that was sold for boiler fuel (5.2 kg) and a very small amount of wood

Table 1. *One-way delivery distance by truck for input materials to particleboard mill.*

Material	Delivery distance (km)
Wood residue	136
Urea–formaldehyde resin	124
Wax	124
Ammonium–sulfate catalyst	124
Urea scavenger	124

Table 2. *Inputs and outputs for the production of 1.0 m^3 of particleboard.*

Production data	Unit	Unit/m^3
Inputs		
Materials		
Wood residue[a]		
Green hog chips	kg	60
Dry hog chips	kg	49
Green shavings	kg	32
Dry shavings	kg	405
Green sawdust	kg	92
Plywood trim	kg	30
OSB fines	kg	3.1
Total wood residue	kg	672
Urea–formaldehyde (UF) resin[b]	kg	68
Wax[b]	kg	2.5
Ammonium–sulfate catalyst[b]	kg	0.72
Urea scavenger[b]	kg	2.9
Electricity		
Electricity	MJ	569
Fuels		
Natural gas	m^3	30
Sander dust (wood)	kg	25
In-mill generated wood fuel	kg	2.1
Diesel	L	0.26
LPG	L	0.33
Gasoline and kerosene	L	0.021
Distillate fuel oil	L	0.057
Water use		
Municipal water source	L	304
Outputs[c]		
Particleboard	kg	746
Wood boiler fuel sold	kg	5.2
Wood waste to landfill	kg	0.4
Boiler fly ash to landfill	kg	0.1

[a] All wood weights given as oven dry.
[b] Weight at 100% solids.
[c] Emissions to air and water listed in separate table.
LPG, liquid propane gas.

waste (0.4 kg) was sent to the landfill. All wood weights are given as oven dry.

The mass balance found a difference between input and output wood materials of particleboard, boiler fuel, and wood waste with slightly more wood going out than coming in. This difference is within the acceptable 5% limit of the CORRIM protocol.

MANUFACTURING ENERGY

Sources of Energy

Energy for the production of particleboard comes from electricity and fuels of wood, natural gas, and oil, whereas other fuels such as diesel, liquid propane gas, and gasoline are used to operate equipment. With the volatile and increasing fuel and electricity prices, this topic will attract considerable attention in the coming years as mills seek to maintain profitability by reducing costs. Also, with the installation of emissions control systems to meet PCWP MACT regulations (USEPA 2004), there is increased use of natural gas and/or electricity to operate these systems resulting in increases of CO_2 fossil emissions. The electricity is used to operate equipment within the plant; equipment such as conveyors, refiners, chippers, fan motors, hydraulic motors, sanders; and emission control devices. The fuels for equipment are used for loaders and forklifts, and the natural gas is used to operate rotary dryers and heat presses. Wood fuel is used in boilers to generate process heat for presses and dryers and is used to direct fire dryers.

Electricity Use

The source of fuel used to generate the electricity used in the manufacturing process is very important in determining the type and amount of environmental impact as a result of its use. The electricity use on average was 569 MJ/m^3 (158 kWh/m^3). The breakdown of fuel source to generate the electricity was based on the US average as stated by the Energy Information Administration (EIA 2007) for 2004. The dominant fuel source is coal at 49.8% followed by nuclear at 19.9% and natural gas at 17.9%. The less contributing sources are hydroelectric at 6.8%, petroleum at 3.0%, and other renewables at 2.3%; much smaller quantities are produced by other gases (0.4%) and other (0.2%). The fuel source to generate electricity is important in any LCI because the impacts are traced back to the in-ground source of the fuel used. The efficiency to produce and deliver electricity is relatively low; generation is about 30% energy-efficient and line loss for delivery is about 7%. In PRé Consultants' SimaPro environmental assessment software, no impacts are associated with hydrogenerated electricity, whereas combustion of coal and natural gas contribute significant impact values. The generation of electricity by fuel source is used to assign environmental burdens in the SimaPro modeling of the various processes.

Fuel Use as a Heat Source

Natural gas is the primary fuel used in the particleboard process; it is used for drying the wood furnish, heating steam or oil for hot presses, and for combusting VOCs and HAPs in emission control systems. All mills use dryers and hot presses, whereas three of the five mills reported using VOC and HAP emissions control systems, which use natural gas and electricity for their operation. With implementation of PCWP MACT rules, the remaining two mills in the study will have likely installed some type of emission control system. The mills reporting use of VOC and HAP emission control systems used RTOs for controlling emissions from dryers and presses. Wood is used for fuel in the form of sander dust that is generated in the process when the panel is sanded to thickness and smoothness; a small amount of additional wood fuel was generated during processing. Three of the five mills used sander dust to fire dryers in addition to the use of natural gas. The sander dust contains about 5% moisture based on its oven-dry weight. One of the mills used wood residue generated throughout the process to heat dryers in addition to their use of sander dust. Another mill used a small quantity of fuel oil to heat dryers. In addition, a small amount of fuel was used to operate forklift trucks and handlers within the mill. Table 3 gives the energy use on-site for manufacturing particleboard. The fuel use for process heat is 1730 MJ/m^3 of which 568 MJ/m^3 (33%) is generated through the combustion of wood fuel a sustainable, renewable resource as opposed to oil and natural gas fuels that are neither sustainable nor renewable. In terms of the total energy use of 2319 MJ/m^3, which includes all fuels and electricity, the wood fuel energy represents 24%. The nonwood energy components of primarily natural gas and electricity use represent an opportunity for improving sustainability by substituting for them with wood fuel.

On-Site Mill Emissions

Outputs for the production of particleboard include a small quantity (0.7%) of coproduct in the form of wood fuel sold to other mills and emissions to air, water, and land (Table 4). Emissions to air include particulate and particulate PM10 (less than 10 μm in size) that occur in refining, drying, sawing, and sanding. Other air emissions include the VOCs and HAPs that occur in drying, pressing, and panel cooling; the HAPs are comprised of acetaldehyde, acrolein, formaldehyde, methanol, phenol, and propionaldehyde. All mills in the survey reported VOC, HAP, formaldehyde, and methanol, whereas only two mills reported acetaldehyde and phenol, and only one mill also reported acrolein. No mills reported propionaldehyde emissions. Only mills reporting a given emission were included in the weight-averaging for that emission. The sum of all the HAP emissions should add to the total HAP value; however, because there is a difference in the number of mills providing data on individual HAPs, the resulting values differ slightly.

Neither the CO_2 emissions for either the biogenic (wood) and fossil-fuel sources nor methane were reported in the survey; rather, they were determined by entering the fuel for both heat

Table 3. *On-site fuel, electricity, and energy*[a] *use in the manufacture of 1.0 m*^{3} *of particleboard.*

Energy use	Unit	Unit/m^3	MJ/m^3	Percent
Fuel for process heat				
Fossil fuel				
Natural gas	m^3	30	1160	
Distillate fuel oil (DFO)	L	0.06	2.2	
Renewable fuel				
Sander dust	kg	25	525	
In-mill generated wood fuel	kg	2.07	43	
Subtotal			1730	74.6
Fuel for equipment				
Diesel	L	0.26	10.1	
LPG	L	0.33	8.8	
Gasoline and kerosene	L	0.021	0.73	
Subtotal			19.96	0.8
Electricity				
Electricity purchased	MJ	569	569	24.5
Total energy			2,319	100

[a] Higher heating values (HHV) used; coal 26.2 MJ/kg, DFO 45.5 MJ/kg, LPG 54.0 MJ/kg, natural gas 54.4 MJ/kg, Diesel 43.4 MJ/kg, gasoline 54.4 MJ/kg, wood/bark 20.9 MJ/kg, and electricity 3.6 MJ/kWh.
LPG, liquid propane gas.

Table 4. *On-site reported outputs for the production of 1.0 m*^{3} *of particleboard.*

Production output	kg/m^3
Particleboard	746
Coproduct	
Wood fuel (sold)	5.2
Emissions to air[a]	
Carbon dioxide, biogenic[b]	56
Carbon dioxide, fossil (GHG)[b,c]	57
Carbon monoxide	0.17
Methane (GHG)[b]	0.0017
Nitrogen oxides	0.18
Sulfur oxides	0.0060
Total VOC	0.36
Particulate	0.21
Particulate (PM10)	0.04
Acetaldehyde (HAP)[c]	0.00063
Acrolein (HAP)	0.000038
Formaldehyde (HAP)	0.055
Methanol (HAP)	0.025
Phenol (HAP)	0.0047
HAPs	0.079
Emissions to water[a]	
Suspended solids	0.010
Emssions to land[a]	
Boiler fly ash	0.10
Wood waste	0.40

[a] Emissions data reported from surveys.
[b] Emissions determined by output from fuel entries into SimaPro for site emissions.
[c] HAP, hazardous air pollutant; GHG, greenhouse gas.
VOC, volatile organic compound.

source and equipment into the SimaPro software. Then the values for carbon dioxide, carbon monoxide, and methane were determined using the FAL database for US fuels. CO_2 biogenic does not contribute to global warming according to the US Environmental Protection Agency because of its life cycle in which it is absorbed by growing of trees, releasing oxygen to the atmosphere and taking the carbon to make wood substance (USEPA 2003). CO_2 biogenic is not counted as a greenhouse gas (GHG) that will impact global warming because the carbon store in wood is continuously renewing.

Cradle-to-Product Gate Resource Use and Emissions

LCI for the production of particleboard covers its cycle from a tree seed as well as the basic components of other additives and in-ground resources through the manufacture of particleboard. It also covers all emissions to air, water, and land. Table 5 gives the raw materials, energy, and emissions for the cradle-to-product gate inventory. The raw materials in the ground include coal, natural gas, limestone, crude oil, uranium, and water use. Materials of small quantities of 1.0E-02 kg/m^3 and less are not included in the listing. Because life-cycle studies involve tracking resource use back to its in-ground source, some materials or substances can involve many steps of backtracking, which results in the use of a large number of substances, many of insignificant quantity. For this study, a filter was used to remove insignificant substances from the listing. The filter varied depending on whether the emission was to air, water, or land. The exception was for substances that are highly toxic such as mercury and uranium (contributed by generation of electricity) in which values less than the cutoff value were recorded.

For recordkeeping only, wood used for fuel is listed, although not a true raw material in the sense its origin as a tree seed. Wood is considered a renewable resource unlike the other materials in the listing; thus, it does not appear in the raw materials listing other than for fuel.

Table 5. *Life-cycle inventory output of allocated emissions cradle-to-product gate for the production of 1.0 m^3 of particleboard.*

Life-cycle inventory	Unit
Raw materials	kg/m^3
Calcite in ground	1.10E-01
Carbon dioxide in air[a]	1.53E+03
Clay in ground	3.16E-02
Coal in ground	5.42E+01
Crude oil in ground	3.55E+01
Gravel in ground	9.28E-01
Iron ore in ground	5.09E-02
Limestone in ground	3.14E+00
Natural gas in ground	9.41E+01
Nickel in ground	2.88E-02
Scrap external	1.79E-02
Sodium chloride in ground	5.90E-02
Tree seeds	5.47E-04
Uranium in ground	2.36E-04
Water unspecified natural origin	7.81E+02
Water, well, in ground	1.25E+02
Wood fuel	1.15E+02
Energy	MJ/m^3
Electricity from other gases	2.63E+00
Electricity from other renewable	1.51E+01
Energy from hydropower	1.95E+02
Emissions to air	kg/m^3
Acetaldehyde (HAP)[b]	1.90E-03
Acetic acid	5.31E-04
Acetone	2.41E-04
Acrolein (HAP)	1.48E-04
Aldehydes, unspecified	9.88E-03
Alpha-pinene	2.48E-03
Aluminum	5.00E-04
Ammonia	1.81E-01
Barium	5.02E-04
Benzene	1.01E-03
Beta-pinene	9.61E-04
Butane	1.04E-03
Carbon dioxide	9.27E-02
Carbon dioxide, biogenic	2.42E+02
Carbon dioxide, fossil (GHG)[b]	3.68E+02
Carbon disulfide	2.09E-04
Carbon monoxide	2.48E+00
Carbon monoxide, fossil	1.54E-01
Chlorine	9.04E-04
Dinitrogen monoxide (GHG)	2.12E-03
Ethanol	1.54E-04
Formaldehyde	6.28E-02
HAPS	7.83E-02
Hydrocarbons, unspecified	5.69E-03
Hydrogen chloride	1.05E-02
Hydrogen fluoride	1.43E-03
Iron	5.95E-04
Lead	1.76E-04
Limonene	2.78E-04

(continued)

Table 5. *Continued.*

Life-cycle inventory	Unit
Manganese	1.04E-03
Mercury	4.25E-06
Methane (GHG)	8.70E-01
Methane, biogenic (GHG)	2.69E-04
Methane, fossil (GHG)	7.33E-02
Methanol	4.86E-02
Naphthalene	2.74E-04
Nickel	4.60E-04
Nitrogen dioxide	6.69E-04
Nitrogen oxides	1.89E+00
Organic substances, unspecified	2.07E-03
NMVOC (nonmethane VOC)	1.15E+00
NOx	2.63E-04
Organic substances, unspecified	1.63E-01
Particulates	2.92E-01
Particulates, <10 μm	4.43E-01
Particulates <2.5 μm	6.07E-02
Particulates, >10 μm	4.73E-02
Particulates >2.5 μm, <10 μm	2.41E-02
Particulates, SPM	1.86E-04
Particulates, unspecified	1.64E-01
Pentane	1.78E-03
Phenol (HAP)	9.27E-03
Potassium	8.90E-02
Propane	3.15E-04
SO_2	4.13E-04
Sodium	2.44E-03
Sulfur dioxide	3.86E-02
Sulfur oxides	4.17E+00
Toluene	3.12E-04
Vanadium	1.34E-03
VOC	6.02E-01
Zinc	5.28E-04
	Bq/m^3
Noble gases, radioactive, unspecified	2.86E+04
Radioactive species, unspecified	2.76E+06
Radon-222	5.53E+04
Emissions to water	kg/m^3
Aluminum	6.08E-04
Ammonia	2.06E-04
Ammonium, iron	1.88E-02
BOD5	1.23E-02
Boron	5.26E-03
Cadmium, ion	2.28E-04
Calcium, ion	4.64E-03
Chloride	2.40E-01
Chromium	2.32E-04
COD	8.17E-02
DOC	9.49E-03
Fluoride	1.03E-02
Formaldehyde	3.24E-03
Iron	7.44E-03
Iron, ion	6.91E-04
Lead	1.10E-05

(continued)

Table 5. *Continued.*

Life-cycle inventory	Unit
Magnesium	1.50E-04
Manganese	4.26E-03
Metallic ions, unspecified	7.73E-04
Methanol	9.73E-04
Nickel, ion	1.58E-04
Nitrogen	6.34E-03
Nitrogen, organic-bound	1.03E-04
Oils, unspecified	8.90E-02
Organic substances, unspecified	1.53E-02
Phenol	3.28E-04
Phosphate	8.28E-03
Phosphorus	3.25E-04
Silicon	3.76E-02
Sodium, ion	5.06E-03
Solids, inorganic	1.74E-04
Solved solids	5.02E+00
Sulfate	2.14E-01
Sulfuric acid	1.31E-03
Suspended solids	1.02E-02
Suspended solids, unspecified	1.53E-01
TOC (total organic carbon)	9.49E-03
Zinc, ion	1.01E-04
Emissions to land	kg/m^3
Boiler fly ash	1.02E-01
Wood waste	3.97E-01
Waste	kg/m^3
Packaging waste paper	2.26E-01
Waste, inorganic	4.34E-01
Waste, solid	4.13E+01
Wood waste	1.27E-01

[a] Includes CO_2 uptake for carbon store in wood component of panel (1290 kg CO_2 equiv) and in wood fuel (242 kg CO_2 equivalent).
[b] HAP, hazardous air pollutant common to wood products industry; GHG, greenhouse gas.
VOC, volatile organic compound; SPM, suspended particulate matter; BOD5, five-day biological oxygen demand; COD, chemical oxygen demand; DOC, dissolved organic carbon.

Some sources of energy or fuels cannot be traced back to their original resource in the ground. Such energies include energy from hydroelectric power, electricity from other gases, and electricity from renewables; these are listed in a separate category defined as "Energy."

Emissions for the cradle-to-product gate scenario are also listed in Table 5. The emissions to air and water used a cutoff value of 1.0E-04 kg/m^3, to land used a cutoff of 1.0E-02 kg/m^3, waste of 1.0E-01 kg/m^3, and radiation used a cutoff of 1E+04 Bq/m^3. Some emissions because of their toxicity, although in quantities below the cutoff value, are recorded. Raw materials and emissions for a cradle-to-product gate inventory are far greater in general than those resources and emissions that occur at the production sites; this is true for all processes. The percentage contribution of on-site to cradle-to-product gate emissions to air is shown by Fig 4. On-site emissions for manufacturing particleboard represent only a small percentage of the total cradle-to-product gate emissions except for formaldehyde, methanol, particulates, phenol, and VOC. HAPs are shown to be solely from the on-site source; however, this is an anomaly in that it was not given in the LCI of wood residue input data but was given in terms of its individual components of acetaldehyde, acrolein, formaldehyde, methanol, and phenol. Most of these emissions are because of wood drying whether in particleboard production or in generation of the input wood residue. On-site CO_2 fossil emissions are only 16% of the cradle-to-product gate emissions.

Of significance is the raw material source of "carbon dioxide in air," which accounts for the uptake of CO_2 during the growing of trees for the wood residue and wood fuel. The CO_2 uptake is accounted for at harvest and is mass-allocated to all wood product, coproduct, and fuel going downstream through the various stages of processing. This uptake is treated as a carbon store in wood for its life cycle. To produce 1.0 m^3 of particleboard, the resource of "carbon dioxide in air" is 1532 kg, which can be used to offset CO_2 emissions from wood and fossil fuel use and some CO_2 in the atmosphere. The breakdown of the CO_2 uptake by contributor is 1290 kg for the CO_2-equivalent of carbon store in the wood component of particleboard and 242 kg for the wood fuel used in the production of wood residue and particleboard. It is common practice in European LCI modeling to account for the carbon store of wood in this manner. An expanded discussion is given subsequently in the "Carbon Flux" section.

Embodied Energy

The embodied energy to produce particleboard can be given in several ways. For this study, it is

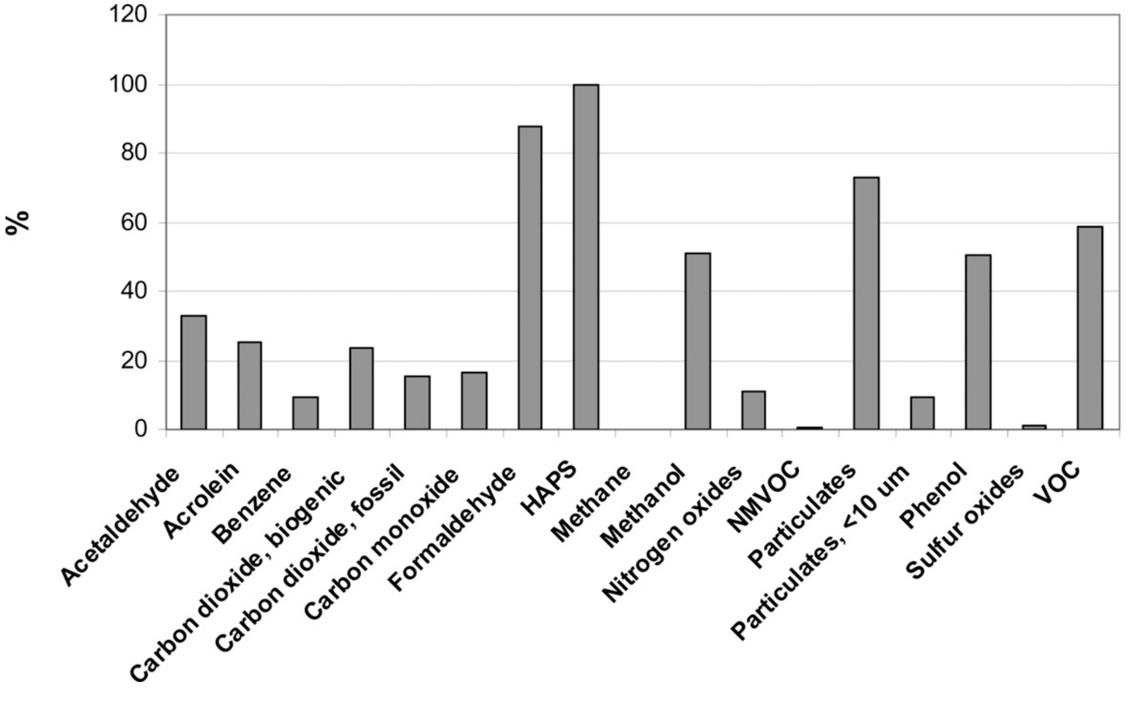

Figure 4. Contributions of on-site to cradle-to-product gate emissions for particleboard.

useful to examine the energy breakdown in terms of both its source of fuel in the ground and its contribution by the various input substances.

Table 6 gives the allocated energy use from cradle-to-product gate for the production of particleboard in terms of its fuel source in the ground. To produce 1.0 m^3 of particleboard, it takes a total of 10,865 MJ of embodied energy based on the HHV of the fuels. Natural gas provides 47.1% of the energy followed by wood fuel at 22.2%, oil at 14.9%, and coal at 13.1%; all other sources are of minor significance. The importance of the wood fuel contribution is that it is renewable and sustainable, whereas the fossil fuel sources of natural gas, oil, and coal are not. An opportunity exists to reduce the use of fossil fuels by substituting for them with renewable wood fuels, at least for some practical portion of the fossil fuels.

Energy contribution by the input component to the manufacturing can be of value in assessing the major contributors and for identifying opportunities for reducing energy use. Table 7 gives the embodied energy breakdown for manufacturing particleboard from tree seed to the exit gate of the mill. The total energy again is 10,865 MJ/m^3 with the inputs of wood residue and UF resin being the major contributors at 32.3 and 28.6%, respectively, followed by electricity and natural gas at 15.8 and 14.1%, respectively, into the manufacturing process. This was followed by wood fuel at 5.2% into the process with all other contributors of lesser significance.

Table 6. *A breakdown by fuel source in terms of their energy values[a] to produce 1.0 m^3 of particleboard cradle-to-product gate.*

Substance	MJ/m^3	Contribution (%)
Coal in ground	1419	13.1
Natural gas in ground	5118	47.1
Crude oil in ground	1616	14.9
Uranium in ground	90	0.8
Wood fuel	2410	22.2
Energy, hydroelectric power	195	1.8
Energy, renewable	15	0.1
Energy, other gases	3	0.02
Total	10,865	100

[a] Energy values based on fuel higher heating values (HHV) of Table 3 and uranium at 381,000 MJ/kg.

Transportation of wood, resin, wax, and scavenger to the mill represents only 2.8% of the total energy. Over 50% of the energy contribution is to produce the wood residue and the UF resin. Energy to provide manufacturing process heat and electricity represents 35% of the total with electricity representing 15.8%.

Sensitivity Analysis

A sensitivity analysis was conducted per ISO protocol that involved examining the impact of varying an input parameter such as fuel to a process and examining the magnitude of the change of an output parameter such as resource use or CO_2 (fossil) emission. The sensitivity analysis first assessed the input parameters such as wood residue, resin, catalyst, wax, scavenger, fuels, electricity, and transportation and their impact on emissions to air, water, and land. A test was done to determine whether changing a specific input such as wood fuel would result in an expected change for output emissions. The magnitude of the impact was found to be dependent on the input parameter and also on the output parameter of interest. For the complete sensitivity analysis, see Wilson (2008).

Carbon Flux, Store, and Footprint

With climate change becoming a major issue, government agencies, companies, and individuals are looking for ways to reduce GHG emissions, which contribute significantly to it. The

Table 7. *A breakdown by energy contributor to produce 1.0 m^3 of particleboard cradle-to-product gate.*

Process component	MJ/m^3	Contribution (%)
Wood residue	3504	32.3
Urea–formaldehyde resin	3105	28.6
Ammonium–sulfate catalyst	26	0.2
Wax	16	0.1
Urea scavenger	88	0.8
Transportation diesel	304	2.8
Natural gas	1529	14.1
Wood fuel	561	5.2
Distillate fuel oil	3	0.0
Electricity	1715	15.8
Diesel and other equipment fuels	13	0.1
Total	10,865	100

major GHG is CO_2 with lesser contributions from methane (CH_4) and nitrous oxide (N_2O), although there are other gases such as fluorinated gases that do not occur in this study. Two possible approaches to reducing GHG emissions include storing carbon so that it is not in the atmosphere in the form of CO_2 and reducing the use of fossil fuels. Carbon flux through a product's life cycle can be used to assess the total impact of CO_2 on global warming and climate change as measured by a sum of its carbon store and carbon footprint.

Carbon is stored in wood whether in trees, products, or fuel. When trees grow, they remove CO_2 from the atmosphere to form wood substance, which is comprised of about half by weight of carbon (C) releasing oxygen (O_2) back into the atmosphere. The carbon remains stored in the wood until it is burned or breaks down because of chemical action or decay. This characteristic of wood to store carbon can be used in a management plan to reduce climate change. Topics of interest on this include the flux of carbon through the processing stages, carbon store in products, and the carbon footprint for both the manufacture of particleboard and the cradle-to-product gate processes.

Carbon in wood was tracked for the production of particleboard in and out of the manufacturing process to determine the balance for its carbon flow. This analysis followed carbon from the inputs of wood materials through production of product, coproduct, waste, and the generation of emissions. The percentage of carbon in wood was taken as an average value for those referenced in earlier CORRIM LCI studies of softwood lumber, plywood, and OSB as 52.4% (Kline 2005; Milota et al 2005; Wilson and Sakimoto 2005), which provided the input wood furnish LCI data. The input consists of wood shavings, sawdust, chips, plywood trim, and OSB fines and the outputs of particleboard, sold wood fuel, and wood-related emissions (Wilson 2008). The wood carbon content of 1.0 m^3 of particleboard is 352 kg. The difference between the inputs and outputs is about 5% with more carbon flow out than in. This difference can be attributed to the variance of the survey data, the accuracy of measuring differences for inputs and outputs, and the FAL database for wood fuel, which predicts slightly more CO_2 than expected.

The CO_2-equivalents (CO_2 equiv) of carbon store in 1.0 m^3 of particleboard is –1290 kg based on 52.4% carbon component of wood (Wilson 2008). The carbon store is treated as a negative value when determining the carbon flux. The CO_2 equiv is determined by the molar mass ratio of CO_2 to C of 44/12 for 3.67 times the carbon content of the wood. Whereas there is also carbon store in other particleboard components of UF resin (25.4% by weight), wax (85%), and urea scavenger (20%), these carbon stores are not counted in the carbon flux values because they are derived from fossil feedstock of oil or natural gas (Wilson 2009, 2010). Only carbon flux values of wood are considered because their carbon cycle is continuously renewing. The carbon cycle of fossil feedstock is not continuously renewing, at least within our time cycle. Wood carbon stores renew within decades, whereas fossil fuels of crude oil and natural gas renew in millions of years. The carbon store remains in the particleboard for the life of its service that can be 10 – 80 yr. The carbon store can be even longer if placed in a modern landfill where much of it can last for an additional 100 yr and more (Skog 2008). When the CO_2 is finally released into the atmosphere, it is reabsorbed by the growing of trees to form more wood, thus continuously renewing the carbon cycle.

The carbon footprint of a product, process, or service is based on the total CO_2 equivalents of GHG emitted. CO_2 emission as a result of the combustion of wood is not included in the footprint because it is offset by its own carbon store; as such, the combustion of wood is considered carbon-neutral. Considering the combustion of wood for fuel as carbon-neutral is consistent with many groups overseeing environmental concerns (USEPA 2003; IPCC 2007; BSI 2008). The carbon footprint includes emissions of CO_2, CH_4, N_2O, and any fluorinated gases in terms of their CO_2 equiv based on their atmospheric 100-yr radiative forcing factors (IPCC 2007). The carbon footprint of particleboard in terms of its kg CO_2 equiv is equal to the kg CO_2 fossil emissions plus 25 times the kg CH_4 emissions plus 298 times the kg N_2O emissions. Figure 5 gives the carbon footprint, carbon store, and net carbon flux for particleboard. The cradle-to-product gate carbon footprint to produce particleboard is 392 kg CO_2 equiv, whereas the on-site footprint for manufacture only is 57.3 kg CO_2 equiv. The on-site footprint is only 15% of the total cradle-to-product gate emissions. Although the carbon equivalent emission of wood fuel combustion is not considered in the carbon footprint, its value is given for illustration purposes because of its carbon store that is considered as a 1:1 offset for its emission.

The carbon store of –1290 kg CO_2 equiv for particleboard can be used to offset the carbon footprint of 392 kg CO_2 equiv to determine the net carbon flux of –898 kg CO_2 equiv cradle-to-product gate (Fig 5). This remaining offset can be used against additional CO_2 emissions beyond the product gate because of product use, disposal, or recycle and possibly against CO_2 in the atmosphere. Because of the large carbon store for particleboard that more than offsets its carbon footprint through manufacturing and beyond, it can be considered a better than climate-neutral material. A climate-neutral material would have a carbon store equal to its carbon footprint.

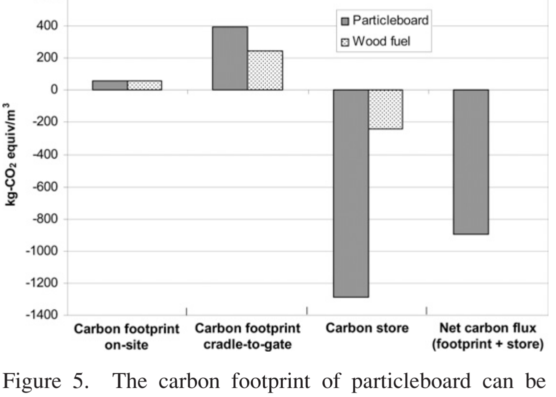

Figure 5. The carbon footprint of particleboard can be offset by its carbon store. Wood fuel is carbon-neutral; its combustion emission is offset by its store.

DISCUSSION

The LCI data documented in this report on the manufacture of particleboard forms a foundation for the scientific assessment of its environmental performance. The data can be used in a number of ways to show particleboard's favorable performance in environmental issues such as sustainability, global warming, climate change, carbon storage, use of wood fuel, green purchasing, and green building. The data can be used as stated or in a life-cycle assessment to determine impacts of process changes and to compare with various alternative materials or assemblies of materials. For comparison of the results of this study to other processes or materials, it is important that they be compared using the same boundary system conditions and when comparing energy using the higher heating values of the fuels.

The International Panel for Climate Change (IPCC) described three strategies associated with wood to reduce CO_2 in the atmosphere; two of the three included the use of wood products (IPCC 1996). They later stated that the substitution effect of wood products for fossil-fuel-intensive products provide cumulative and permanent avoidance of fossil carbon emissions, whereas storage in trees provide limited and possibly transient emissions avoidance. Simply put, it is environmentally more effective to use trees for products that displace fossil-intensive products for reducing carbon emissions to the atmosphere than it is to store the carbon in trees (IPCC 2001a, 2001b). These same strategies can be addressed with the manufacture and use of particleboard in which wood is used as fuel to displace fossil fuels for a significant portion of its energy need and as product to displace fossil-fuel-intensive products.

CONCLUSIONS AND RECOMMENDATIONS

An LCI was developed for the production of 1.0 m^3 of particleboard as produced in the US. The system boundary went from resources in the ground through particleboard manufacture. The quality of the primary data collected by survey questionnaire of particleboard manufacturers was high as judged by assessments for outliers, a mass balance of material, and an energy balance. Primary data were also used for resin and wood residue use from other CORRIM studies. Secondary data were used for inputs of electricity, fuels, and some chemicals. The data set and reporting are in compliance with both CORRIM and ISO protocol and guidelines for LCI studies. As a result of the LCI analyses of both on-site and cradle-to-product gate system boundaries, the following conclusions are made:

- On-site emissions for manufacturing particleboard represent a small percentage of the total cradle-to-product gate emissions except for formaldehyde, methanol, particulates, phenol, and VOC. Most emissions are because of the extraction, processing, and delivery of wood residue, resin, chemicals, fuels, and electricity to the mill. For on-site, the CO_2 emission is comparable for both wood and fossil fuel sources; however, unlike fossil-fuel emission, the wood fuel emission does not contribute to global warming and climate change.
- The embodied energy to produce 1.0 m^3 of particleboard consists of fuels and electricity used on-site and the fuels used cradle-to-product gate that include on-site as well as those fuels to generate and deliver wood, chemicals, fuels, and electricity to the mill. The on-site energy use is 2,319 MJ and the cradle-to-gate energy is 10,865 MJ. Of the on-site energy, the wood fuel contributed 24%. The use of wood fuel is important because it is a sustainable, renewable fuel that is considered global-warming and climate-change neutral that is substituting for fossil fuel, a nonrenewable fuel.
- The favorable effect of carbon storage by both wood and bark carries over into the manufacture of particleboard, which can be used to offset CO_2 emissions not only from cradle-to-gate, but for product use and disposal as well as some CO_2 in the atmosphere. To produce 1.0 m^3 of particleboard, the CO_2 removed from the air because of carbon store is –1290 kg-CO_2 equiv, which can be used to offset the CO_2 equiv of the LCI output GHG emissions of 392 kg CO_2 equiv—that can be considered its carbon footprint—because of the combustion of fossil fuel from in-ground resources through to product. This leaves a net carbon flux of –898 kg CO_2 equiv as a credit to offset CO_2 because of product use and disposal and in the atmosphere, thus reducing its impact on global warming and climate change. This carbon store remains in the particleboard for the life of its service and even longer if recycled or placed in a modern landfill where much of it can last for 100 yr or more. This is consistent with the IPCC that it is environmentally more effective to use trees as fuel and products that displace fossil fuel and fossil-fuel-intensive products than it is to store the carbon in trees.

This study provides a comprehensive database for the LCI of particleboard. The data should be used as the basis for any LCA of its environmental performance to improve processing or to compare with other materials. When comparing the data in this study with other processes and products, it is important to use the same boundary system conditions and fuel energy values. These LCI data will be available to the public in a CORRIM comprehensive report at www.corrim.org (Wilson 2008).

To fully benefit from the availability of the LCI database for particleboard, the following additional studies are recommended: 1) extend LCI data beyond the production gate through its use, disposal, and recycle life; 2) conduct life-cycle assessment studies of particleboard for various uses; 3) extend the study on the impact of increasing the substitution of wood for fossil fuels; and 4) conduct a carbon flux analysis of particleboard beyond the product gate to include use, disposal, and recycle.

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