# LIFE CYCLE IMPACTS OF NORTH AMERICAN WOOD PANEL MANUFACTURING[1]

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(Received August 2015)

**Abstract.** Manufacturing building products such as wood panels impacts the environment, including contributing to climate change. This study is a compilation of four studies quantifying these impacts using the life cycle assessment (LCA) method on five wood-based panel products made in North America during 2012. LCA is an internationally accepted and standardized method for evaluating the environmental impacts of products. With LCA, holistic environmental impacts were calculated based on survey data from mills on emissions to air and water, solid waste, energy consumption, and resource use. This study incorporated cradle-to-gate production of nonwood materials including additives and energy products, such as natural gas and coal, consumed at the production facilities. In addition, primary transport of wood materials to the production facilities was included. These primary data were entered in LCA modeling software on a production unit of 1 $m^3$ of the panel to estimate manufacturing gate-to-gate life cycle inventory (LCI) flows and major environmental impacts. The LCI flows and environmental impacts were converted to a functional unit of 1 $m^2$ of the wood panel (ie final product) produced. The following products were evaluated with their stated panel thicknesses in millimeters: oriented strandboard (9.5), Southeast (SE) and Pacific Northwest (PNW) softwood plywood (9.5), cellulosic fiberboard (12.7), and hardboard (3.2). Results are provided on cumulative primary energy consumption (CPEC) and global warming impacts (GWI). CPEC was 74.0, 73.5 (SE), 68.7 (PNW), 76.0, and 88.3 MJ/$m^2$, with biomass-derived energy percentage of 50, 50 (SE), 64 (PNW), 12, and 47, respectively. GWI was 1.97, 1.90 (SE), 1.23 (PNW), 3.91, and 2.47 kg $CO_2$ equivalent/$m^2$, respectively. Densities and panel thicknesses have the greatest impacts on converting from a cubic meter to a square meter basis. The panel products evaluated here are mostly not interchangeable. Thus, results for the panel products should not be compared. Using woody biomass energy for panel production decreases their contribution to climate change.

***Keywords:*** Wood panels, environmental performance, GHG, climate change, building materials.

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*Wood and Fiber Science*, 48(2015 Convention, Special Issue), 2016, pp. 40-53

## INTRODUCTION

The manufacture of building products such as wood panels impacts the environment, including contributing to climate change. Evaluating these impacts would help in identifying environmental "hot spots" and producing building products with lower environmental impacts. Buildings consume approximately 41% of all energy used in the United States (USDOE 2014). Although much energy is used during building occupation, there is increased interest in decreasing the embodied energy—the amount of energy used in manufacturing of building components—as part of the overall goal of decreasing the environmental footprint of buildings.

"Green" construction practices have evolved considerably during the past 30 years in an effort to decrease energy consumption, improve overall building performance, and move toward more sustainable practices. In practice, green building began as a series of prescriptions that experts thought were the most vital to move construction toward sustainability goals. Green building has now grown to include life cycle assessment (LCA), which provides insight to improving energy and material efficiency throughout material production and building construction and operation and lowering the overall environmental burdens throughout the building's whole life cycle (Sartori and Hestnes 2007; Ramesh et al 2010; Bowyer et al 2012).

LCA is the internationally accepted and standardized method for evaluating the environmental impacts of products. LCA is a scientific approach to measuring the holistic environmental impacts of a product, including resources consumed and emissions released along with the associated environmental impacts. An LCA can cover the life of a product from extraction of raw materials to product production point (ie cradle-to-gate) or through distribution, use, and to its final disposal point (ie cradle-to-grave) (Fig 1) (ISO 2006a, 2006b; Wolf et al 2012). In addition, LCA of products are incorporated into environmental footprint software for building professionals (architects and engineers) such as the Athena Impact Estimator (Athena Sustainable Materials Institute, Ottawa, Ontario, Canada) for Buildings (ASMI 2015). Conducting whole building LCA provides for points that go toward green building certification in rating systems such as Leadership in Energy and Environmental Design, Green Globes, and the ICC-700 National Green Building Standard (Ritter et al 2011). Points from product LCA are typically assigned in the material resource and efficiency part of the rating systems.

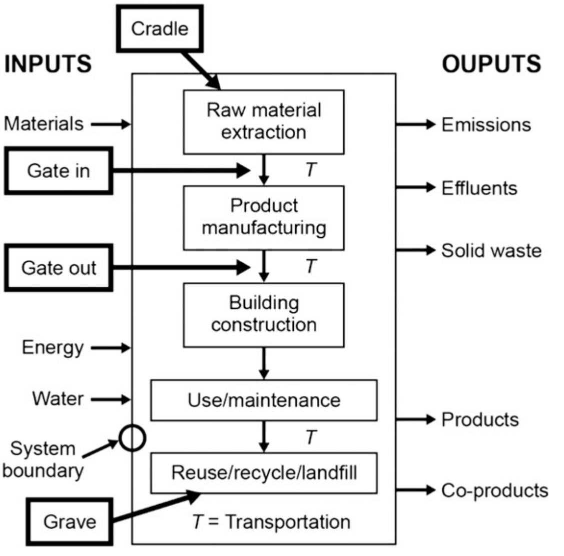


Figure 1. Complete life cycle from regeneration of trees to disposal of wood materials.

LCA comprise four stages (phases) as defined by the International Organization of Standardization (ISO): 1) goal and scope definition, 2) life cycle inventory (LCI) analysis, 3) life cycle impact assessment (LCIA), and 4) interpretation (Fig 2). An LCA study includes all stages, but an LCI study does not include stage 3. The goal and scope provide the study framework and explain how and to whom results are to be communicated.

The LCI measures all raw materials and energy inputs and associated environmental outputs to manufacture a particular product, process, or service on a per-unit basis within carefully defined system boundaries. LCI are typically data- and time-intensive activities. Many earlier LCA for North American wood products were

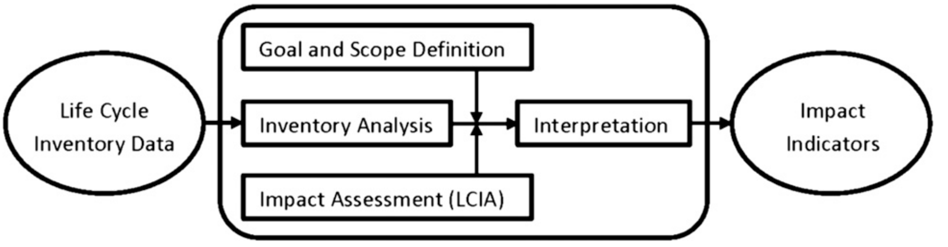


Figure 2. Four stages of life cycle assessment.

LCI studies, not full LCA studies, and therefore, did not include the LCIA phase (CORRIM, *Wood and Fiber Science* Special Issues 2005, 2010). The main focus of these earlier LCI studies was to help develop and populate LCI databases that could be used by other LCA practitioners. The LCIA use LCI flows to examine impacts for four areas: human health, social health, resource depletion, and ecosystem function. In the interpretation stage, alternatives for action to decrease impacts are systematically evaluated (ISO 2006a, 2006b; Wolf et al 2012).

Documenting the environmental performance of building products also is a response to false or misleading green marketing claims (ie “green washing”). Developing environmental product declarations (EPD) for building products is a systematic way to provide relevant evidence-based documentation and to counter green washing (ISO 2006c, 2007; Bergman and Taylor 2011). An EPD is a summary of environmental impacts associated with manufacturing and using a product or service. EPD, often referred to as LCA-based eco-labels, are based on LCI data and the environmental impact factors produced using LCA techniques with that data (ISO 2006c). EPD are analogous to nutritional labels on food items; they can be used to compare products on an equal basis. EPD are intended to provide standardized LCA data in a way that are meaningful to people who may not be familiar with the details of LCA (Bergman and Taylor 2011).

For consistency, building product EPD are developed according to ISO standards and where applicable to specified product category rules (PCR). PCR are common and harmonized calculation rules used to ensure that similar procedures are consistently applied when creating or comparing EPD. An EPD can be either business-to-business (BtoB) or business-to-consumer (BtoC). An EPD must be independently verified when it is used for BtoC communication, and a verifier must therefore be identified and retained. In general, the verifier confirms that the LCA has been done in accordance with the PCR, that all required documentation is in place to make the EPD transparent, and that the underlying PCR meets international standards (ISO 2007).

Product groups usually differ in their inherent environmental performance and therefore require their own PCR. Several years ago, efforts in this arena produced a PCR for North America Wood Products (NA PCR), which was recently revised based on internal and external reviews (FPI 2013, 2015). The NA PCR identifies the data and approach that must be taken when developing EPD for North American wood products. It includes specifications on impact metrics, age of the data, system boundaries, functional units, and unit processes to include in the assessment.

The goal of this study is to compile and document the gate-to-gate LCA of wood panel production for North America for oriented strandboard (OSB), softwood plywood, cellulosic fiberboard, and hardboard. The resultant data will be linked to forest resource data to develop cradle-to-gate LCA and then create or update BtoB EPD. Softwood plywood was evaluated on a regional basis for the Southeast (SE) and Pacific Northwest (PNW) of the United States. Hardboard panel product includes engineered wood siding and trim (EWST). In this study, hardboard and EWST are considered the same composite wood product category and will be referred to as just hardboard for simplicity. Some LCI analyses on cellulosic fiberboard and hardboard have been completed and were included in this study for development of environmental performances (Bergman 2014a, 2014b, 2015a, 2015b). The compiled studies evaluated material flow, energy consumption, and emissions for the wood panel manufacturing process on a per-unit basis of 1 $m^3$. Primary data were collected by visiting the wood panel manufacturers and administering a questionnaire. Peer-reviewed literature referencing preexisting LCI datasets provided secondary data per Consortium for Research on Renewable Industrial Material (CORRIM) guidelines (CORRIM 2014). Wood mass balances were constructed with a spreadsheet algorithm using data from primary and secondary sources. From material and energy inputs and reported emissions, SimaPro 8 software (PRé Consultants, Amersfoort, the Netherlands) was used to model the estimates for raw material consumption and environmental outputs on a per-functional unit basis (PRé Consultants 2015). The complied studies used the US LCI Database for secondary LCI data inputs such as fuels and electricity (NREL 2012).

To quantify the various impacts from air and water emissions released to the atmosphere during product production, the categorized LCI flows are characterized into common equivalence units that are then summed to provide an overall impact category total. Different impact categories cover different emissions (ie LCI flows). For assessing the environmental impacts of wood panel production, the tool for the reduction and assessment of chemical and other environmental impacts (TRACI) impact method was used. TRACI is a midpoint-oriented LCIA method developed by the US Environmental Protection Agency specifically for the United States using input parameters consistent with US locations (Bare 2011). TRACI is available through the LCA software used for modeling the wood panel production processes (PRé Consultants 2015). This study includes the LCIA impact categories of global warming (kg $CO_2$-eq), acidification (kg $SO_2$-eq), eutrophication (kg N-eq), ozone depletion (kg CFC-11-eq), and smog (kg $O_3$-eq). Other impact measures included cumulative (total) energy demand (primary energy) (MJ-eq), including both biomass and fossil fuel contributions, which were calculated and reported directly from LCI flows. The individual studies also tracked fresh water consumption (in liters) and renewable and nonrenewable material resource consumption (nonfuel resources). Impact categories and other impact measures were reported per 1 $m^2$ and 1 $m^3$ of production.

Previous LCA studies have been completed in the United States on some softwood panel products. LCI flows for OSB and softwood plywood were estimated more than 10 yr ago and thus must be reinventoried for documentation for LCA-based eco-labels referred to as EPD (ISO 2006c; Bergman and Taylor 2011; FPI 2013). The original US LCI studies (Kline 2005; Wilson and Sakimoto 2005) were updated as part of a larger research effort into LCA on softwood plywood and OSB (Kaestner 2015). US LCI data on cellulosic fiberboard and hardboard has just been more recently developed (Bergman 2014a, 2014b, 2015a, 2015b). The objective of this study was to compile recent manufacturing life cycle stage studies and present LCIA outcomes on five wood-based panels in North America.

## METHOD

This study is a compilation of four studies quantifying environmental impacts using the LCA method on five wood-based panel products made in North America during 2012. An attributional LCA (ALCA) approach was conducted by the individual life cycle studies compiled. There are two basic process-modeling methods used in LCA. ALCA uses the process-modeling method to find the critical environmental impacts for a particular product referred to as cradle-to-grave (raw material extraction to waste disposal) analysis (Thomassen et al 2008; Gaudreault et al 2010). As an alternative, consequential LCA (CLCA) is a process-modeling method but is used to describe the (indirect) consequences of a particular decision. CLCA estimates system-wide changes in (material and energy) resource flows and environmental burdens that result from different production levels of the functional unit based on a decision (Ekvall and Weidema 2004; Ekvall and Andrae 2006).

## Scope

This study covered the manufacturing stage of wood panel production from forest landing to final product leaving the mill according to ISO (2006a, 2006b; Wolf et al 2012). LCA data from this study will help conduct a cradle-to-gate LCA for wood panels in preparation for developing EPD, a Type III LCA-based eco-label (ISO 2006c). To construct a cradle-to-gate LCA, this gate-to-gate manufacturing LCA will be linked to forest resources (upstream) LCA data from the US LCI Database (NREL 2012). This manufacturing stage LCA provided an analysis of cumulative primary energy of manufacturing and transportation of raw materials to production facilities. This study included the cumulative primary energy consumption (CPEC) of the five wood panels and the five LCIA impact categories previously listed.

## Manufacturing Process

For most wood panels, woody biomass residues that were historically burned for energy or were sent to landfills for disposal as waste material are now used in the manufacturing of the panels. During the last several decades, these wood panel products have evolved into highly engineered products designed to meet specific end-use requirements. The production of wood panels falls into the North American Industry Classification System Code 321219—reconstituted wood products, which include other wood composite products such as cellulosic fiberboard, medium-density fiberboard, particleboard, and OSB (USCB 2012). This study does not make a distinction between hardboard and EWST except for the standards used to produce these products. EWST are composite panels designed and manufactured to perform in applications with the appearance of traditional wood.

Manufacturing engineered wood products such as wood panels requires electricity for breaking down wood raw material (ie feedstock) and thermal energy to dry wood raw material and set resins. These inputs are primarily responsible for most of the greenhouse gas (GHG) emissions released to the atmosphere during wood product manufacturing (Puettmann and Wilson 2005; Puettmann et al 2010; Bergman et al 2014). Amount and type of thermal energy depends on the panel product's manufacturing process, whereas the electricity profile depends on the location of the plants and the associated energy sources (USEPA 2014). Regarding contributions to climate change (ie global warming), the impact of carbon stored in the final product compared with the manufacturing GHG emissions was investigated. The following describes the individual panel production processes.

***Oriented strandboard.*** OSB is an engineered structural panel produced from wood strands and bounded with resin (Stark et al 2010). The initial production step requires roundwood, which is debarked and processed into wood strands. The produced green strands are dried with thermal energy produced by by-products, such as wood residues or bark, and fossil energy sources. After the screening process, in which fines and strands that are too small are removed, the strands are blended with resin. The commonly used resin systems are phenol formaldehyde and methylene diphenyl diisocyanate. The blended flakes are formed to a mat with cross-directional layers and are pressed under the combination of pressure and temperature to produce a rigid and dense board. The OSB boards are cooled, sawn to appropriate size, grade stamped, staked in bundles, and packaged for shipping. The significant thermal energy needed for production is mainly met by burning wood by-products (Kline 2005; Puettmann et al 2013a; Kaestner 2015). For cleaning process air, emission control devices, which require a significant amount of gas or electricity, are used. OSB is the only product produced at the production facility.

***Softwood plywood.*** Softwood plywood is manufactured of cross-directional layers of peeled veneer and glued together with resin.

The delivered logs are debarked and conditioned with hot water or steam to soften the wood structure for the peeling process. The logs are peeled in the lathe, clipped and sorted by MC. The green veneer gets dried to an MC of 4-8%. In the layup process, resin is applied on the veneer and panels are composed for the hot-pressing process. After pressing, the panels are sawn to appropriate dimensions, stacked in bundles, and packaged for shipping. Burning wood by-products and fossil energy sources meets most of the thermal energy needed for conditioning, drying, and pressing (Wilson and Sakimoto 2005; Puettmann et al 2013b, 2013c; Kaestner 2015). The plywood mills produce a small amount of veneer that is sold as an intermediary product (allocation is by mass).

***Cellulosic fiberboard.*** Cellulosic fiberboard is produced from industrial wood residues (such as shavings, sawdust, and chips from primary log breakdown), from whole-tree chips, and from mixed paper and construction waste. Manufacturing cellulosic fiberboard uses a wet process that produces a low-density wood composition panel and is often referred to as insulation board. Density for final products ranges from 190 to 380 kg/m$^3$ (Suchsland and Woodson 1986; USEPA 2002; Stark et al 2010; ASTM 2012). A thermomechanical process reduces the wood raw material and binds the fibers with a starch for recombination into cellulosic fiberboard. Wood raw materials include virgin as well as recycled wood such as construction waste and mixed paper (Bergman 2014a 2015a). Other additives may include alum, clay, and wax. Asphalt is added in the mix to improve strength properties. In addition, cellulosic fiberboard may be coated with asphalt for exterior uses. Adding water to the fiber creates a slurry (similar to the paper-making process) that is then transformed into a fiber mat. Presses and large dryers are used to remove water; this process also releases volatile organic compounds. Water usage is of particular concern because plants operating in the 1980s without any water conservation were estimated to consume 22,700 L of water per m$^3$ of cellulosic fiberboard produced (Suchsland and Woodson 1986). Cellulosic fiberboard, often called insulation board, is the only product produced at the production facilities. The final product is used for roofing, sheathing, and sound boards.

***Hardboard.*** Manufacturing hardboard in North America currently uses either a wet or dry process to create high-density wood composition panels (CPA 2012a, 2012b). In the past, hardboard was produced in North America using a semidry process, but this process is no longer used. The semidry process was used to lower resin and water usage while maintaining more of the properties found in wet-process hardboard (Myers 1986). Density for final products ranges from 800 to 1100 kg/m$^3$ (USEPA 2002; Bowyer et al 2007; Gonzalez-Garcia et al 2009; Stark et al 2010). Thermomechanical processes reduce the wood chip raw material to fibers. Resins are added to the fiber before or during mat forming, and then the (dry or wet) mats are pressed to create the hardboard panel. Hardboard may be "tempered" with oil and heat after pressing to improve water resistance properties (Suchsland and Woodson 1986). Hardboard is the only product produced at the production facility. Final products made from uncoated hardboard, commonly called dealer board, include case goods, paneling, and pegboard.

## Functional and Declared Unit

Defining system boundaries sets the unit processes to include standardized material flows, energy use, and emission data. In the individual studies, a declared unit was used because the function and reference scenario for the whole life cycle of the products could not be stated (ISO 2006b; 2007). LCIA results from the compiled studies used a declared unit of 1.0 m$^3$ for reporting to allow for creation of North American wood panel EPD (FPI 2013). This study selected a functional unit of 1.0 m$^2$ of wood panels with a specified basis for comparison. In the United States, industry commonly reports wood panel production in square feet with the thickness whereas the European Union reports the data in

Table 1. Reference flows for North American wood panels, 1 m$^2$.

| Wood panel | Density (oven-dry kg/m$^3$) | Panel thickness (mm) | Reference flow (m$^3$) | Density (oven-dry kg/m$^2$) | Carbon stored (kg/m$^2$) |
|---|---|---|---|---|---|
| Oriented strandboard, southeast United States | 597 | 9.5 | 0.0095 | 5.67 | 2.84 |
| Softwood plywood, southeast United States | 517 | 9.5 | 0.0095 | 4.91 | 2.46 |
| Softwood plywood, Pacific Northwest United States | 458 | 9.5 | 0.0095 | 4.35 | 2.18 |
| Cellulosic fiberboard, North America | 254 | 12.7 | 0.0127 | 3.23 | 1.61 |
| Hardboard, North America | 786 | 3.2 | 0.0032 | 2.52 | 1.26 |

cubic meters (ECJRC 2014; APA 2015; EPF 2015). Table 1 lists the reference flows for the wood panels (Bergman 2014a, 2014b, 2015a, 2015b; Kaestner 2015). The provided reference flows transformed the declared unit into specific product flows for the product systems given the varying panel thicknesses for different wood panel products. Panel thickness varied 3.18-12.7 mm for the various wood panel products studied. In addition, carbon stored per square meter was included in this study for a comparison with manufacturing GHG emissions. The life cycle impacts were reported per 1.0 m$^3$ and 1.0 m$^2$ of final product.

### System Boundary

Boundary selection helps to track the material and energy flows crossing the boundary. To track flows tied to wood panel production, cumulative instead of on-site system boundaries were considered (Fig 3). On-site system boundaries track only what occurs at the production site, whereas a cumulative system boundary includes what happens not only on-site but off-site as well, including fuel resources used for cradle-to-gate

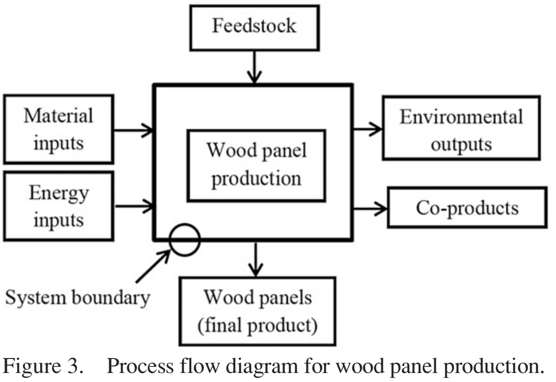


Figure 3. Process flow diagram for wood panel production.

production of energy, additives, and grid electricity. Off-site emissions come from transporting feedstocks and additives, electricity generation, and fuels produced off-site but consumed on-site. Ancillary material data, such as motor oil and greases, were collected and were part of the analysis.

### Data Quality

To ensure high-quality data, the goal of this study was to survey a minimum of 20% of wood panel production in the given wood panel industry. Survey data were collected from OSB, softwood plywood, cellulosic fiberboard, and hardboard manufacturers that represented panel production of 33%, 43%, 96%, and 42%, respectively. Manufacturing plants providing survey data out of total operating plants in 2012 for OSB, softwood plywood, cellulosic fiberboard, and hardboard were eight of 38 (21%), 17 of 53 (32%), eight of nine (89%), and four of seven (57%), respectively (CPA 2013; NAFA 2013; APA 2015).

The researchers collected process-specific (ie primary) annual data from each production facility wherever possible. Primary data obtained from the surveyed mills were weight averaged (Milota 2004):

$$\bar{P}_{weighted} = \frac{\sum_{i=1}^{n} P_i x_i}{\sum_{i=1}^{n} x_i} \tag{1}$$

where $\bar{P}_{weighted}$ is the weighted average of values reported by the mills, $P_i$ is reported mill value, and $x_i$ is the fraction of the mill's value to total production of the surveyed mills for that specific value.

Missing data were defined as data not reported in surveys by the wood panel production facilities.

Whenever missing data occurred for survey items, they were checked with the plant personnel to determine if it was an unknown value or zero. Missing data were carefully noted to prevent them from being averaged as zeros. Any outliers were resolved by contacting mill personnel.

This study collected data from representative wood panel product manufacturers in North America that use average technology for their regions. Primary data for the LCI were collected through surveys in accordance with CORRIM (2014) research guidelines and ISO (2006a) standards. The production facilities surveyed were selected to be representative of North American or their regional production practices.

### Allocation Rules

All allocations were based on the mass of products and coproducts.

### Cutoff Rules

According to the PCR for North American Structural and Architectural Wood Products (FPI 2013, 2015), if the mass/energy of a flow is less than 1% of the cumulative mass/energy of the model flow, then it may be excluded, provided its environmental relevance is minor. This analysis included all energy and mass flows for primary data.

In the primary surveys, manufacturers were asked to report total hazardous air pollutants specific to their wood products manufacturing process. These include formaldehyde, methanol, acrolein, acetaldehyde, phenol, and propionaldehyde (propanal).

### Assumptions and Limitations

Assumptions and limitations can include omissions of life cycle stages, processes, and input or output flows. For the individual studies, human labor and the manufacturing LCA of the machinery and infrastructure were outside the system boundaries and therefore were not included. In addition, the compiled studies only included gate-to-gate manufacturing LCI data. Therefore, no cradle-to-grave LCA was conducted because it was beyond the scope of this study. Although the downstream life cycle stages such as panel product transportation, construction, and disposals such as landfilling were not included in the analysis, they can be included in the future to create a cradle-to-grave LCA such as Bergman et al (2013) conducted for redwood decking. Furthermore, although analyzing wood panels as part of wall assemblies would provide useful information, analyzing wall assemblies was beyond the scope of this study.

## RESULTS AND DISCUSSION

For the individual studies compiled for this study, detailed primary survey data on mass flow, energy consumption, and fuel types were obtained using wood panel surveys. These data were organized with upstream process data for grid electricity and other inputs included in the SimaPro analysis and databases to produce the LCI and LCIA data for the five wood panel products: OSB, SE and PNW softwood plywood, cellulosic fiberboard, and hardboard. The weight-averaged survey data were then modeled to estimate nonwood raw material use, emission data, and environmental impacts on a 1-m$^3$ and 1-m$^2$ unit basis as required. With SimaPro 8, the life cycle data were compiled into impact measures using the TRACI (Bare 2011) impact estimation method. The other renewables category included wind, solar, geothermal, and hydroelectric. Primary energy is the energy embodied in the original resources such as crude oil and coal before conversion and was reported as CPEC.

Table 2 shows environmental impacts of producing 1 m$^3$ of wood panels. CPEC for wood panel production on a cubic meter basis varied widely from 5.98 to 27.6 GJ/m$^3$ considering the range of the thicknesses for the wood panels. Hardboard by far consumed the greatest total primary energy during product production when gauged on a volume basis, albeit it was the thinnest and densest wood panel studied (Table 1).

Table 2. Life-cycle impacts of 1 $m^3$, wood panels, U.S. average, gate-to-gate (mass allocation).

| Impact category | Unit | OSB[1] | SE[2] | PNW[2] | CF[3] | HB[4] |
|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$-eq | 207 | 200 | 129 | 302 | 772 |
| Acidification | kg $SO_2$-eq | 2.11 | 2.0 | 1.5 | 8.4 | 26.6 |
| Eutrophication | kg N-eq | 9.99E-02 | 5.68-02 | 5.03E-02 | 4.39E-01 | 2.13E+00 |
| Ozone depletion | kg CFC-11-eq | 6.36E-07 | 1.24E-07 | 1.01E-07 | 1.00E-05 | 8.53E-05 |
| Smog | kg $O_3$-eq | 28 | 22 | 20 | 214 | 772 |
| Primary energy consumption | Unit | | | | | |
| Nonrenewable, fossil | MJ | 3360 | 3339 | 2222 | 4488 | 12578 |
| Nonrenewable, nuclear | MJ | 483 | 495 | 235 | 457 | 1869 |
| Renewable, other | MJ | 52 | 29 | 147 | 294 | 203 |
| Renewable, biomass | MJ | 3891 | 3872 | 4631 | 730 | 12956 |
| Total Primary Energy | MJ | 7789 | 7737 | 7232 | 5984 | 27594 |
| Material resources consumption (Nonfuel) | Unit | | | | | |
| Nonrenewable materials | kg | 5.3 | 3.2 | 6.3 | 3.1 | 33.4 |
| Renewable materials | kg | 523 | 744 | 673 | 244 | 883 |
| Fresh water | L | 153 | 704 | 635 | 1299 | 11234 |
| Waste generated | Unit | | | | | |
| Solid waste | kg | 3.4 | 12.5 | 62.9 | 5.7 | 42.5 |

Table 3 shows environmental impacts of producing 1 $m^3$ of wood panels on a percentage basis. Hardboard had the greatest environmental impacts relative to the other wood panels for all life cycle impacts except for the following categories: 1) other renewable sources (cellulosic fiberboard) and 2) solid waste (PNW softwood plywood). Cellulosic fiberboard consumed the lowest percentage of renewable biomass, which is consistent with the results shown in Table 2. This was primarily because of cellulosic fiberboard production can use low-quality feedstock that other wood panel products would use as fuel for boilers (Bergman 2014a, 2015b). Therefore,

Table 3. Life cycle impacts of 1 $m^3$, wood panels, US average, gate-to-gate (mass allocation), percentage basis.

| Impact category | Percentage | OSB[a] | SE[b] | PNW[b] | CF[c] | HB[d] |
|---|---|---|---|---|---|---|
| Global warming | (%) | 26.9 | 25.9 | 16.8 | 39.1 | 100 |
| Acidification | (%) | 7.9 | 7.5 | 5.5 | 31.7 | 100 |
| Eutrophication | (%) | 4.7 | 2.7 | 2.4 | 20.6 | 100 |
| Ozone depletion | (%) | 0.7 | 0.1 | 0.1 | 11.7 | 100 |
| Smog | (%) | 3.6 | 2.9 | 2.6 | 27.7 | 100 |
| Primary energy consumption | | | | | | |
| Nonrenewable, fossil | (%) | 26.7 | 26.5 | 17.7 | 35.7 | 100 |
| Nonrenewable, nuclear | (%) | 25.9 | 26.5 | 12.6 | 24.4 | 100.0 |
| Renewable, other | (%) | 17.5 | 10.0 | 50.0 | 100 | 69.0 |
| Renewable, biomass | (%) | 30.0 | 29.9 | 35.7 | 5.6 | 100 |
| Total primary energy | (%) | 28.2 | 28.0 | 26.2 | 21.7 | 100 |
| Material resources consumption (nonfuel) | | | | | | |
| Nonrenewable materials | (%) | 15.7 | 9.4 | 18.9 | 9.2 | 100 |
| Renewable materials | (%) | 59.3 | 84.3 | 76.2 | 27.7 | 100 |
| Fresh water | (%) | 1.4 | 6.3 | 5.6 | 11.6 | 100 |
| Waste generated | | | | | | |
| Solid waste | (%) | 5.4 | 19.9 | 100 | 9.0 | 67.5 |

[a] 9.5-mm-thick oriented strandboard (OSB).
[b] 9.5-mm-thick softwood plywood (SE, Southeast; PNW, Pacific Northwest).
[c] 12.7-mm-thick cellulosic fiberboard (CF).
[d] 3.2-mm-thick hardboard (HB)/engineered wood siding and trim.

Table 4. Life cycle impacts of 1 $m^2$, wood panels, US average, gate-to-gate (mass allocation), quantity basis.

| Impact category | Unit | OSB[a] | SE[b] | PNW[b] | CF[c] | HB[d] |
|---|---|---|---|---|---|---|
| Global warming | kg $CO_2$-eq | 1.97 | 1.90 | 1.23 | 3.83 | 2.47 |
| Acidification | kg $SO_2$-eq | 0.020 | 0.019 | 0.014 | 0.107 | 0.085 |
| Eutrophication | kg N-eq | 9.49E-04 | 5.40E-04 | 4.78E-04 | 5.58E-03 | 6.81E-03 |
| Ozone depletion | kg CFC-11-eq | 6.04E-09 | 1.18E-09 | 9.60E-10 | 1.27E-07 | 2.73E-07 |
| Smog | kg $O_3$-eq | 0.264 | 0.209 | 0.189 | 2.72 | 2.47 |
| Primary energy consumption | Unit | — | — | — | — | — |
| Nonrenewable, fossil | MJ | 31.92 | 31.72 | 21.11 | 57 | 40.25 |
| Nonrenewable, nuclear | MJ | 4.59 | 4.70 | 2.23 | 5.80 | 5.98 |
| Renewable, other | MJ | 0.49 | 0.28 | 1.40 | 3.74 | 0.650 |
| Renewable, biomass | MJ | 36.96 | 36.78 | 43.99 | 9.27 | 41.46 |
| Total primary energy | MJ | 74.0 | 73.5 | 68.7 | 76.0 | 88.3 |
| Material resources consumption (nonfuel) | Unit | — | — | — | — | — |
| Nonrenewable materials | kg | 0.05 | 0.03 | 0.06 | 0.039 | 0.107 |
| Renewable materials | kg | 4.97 | 7.07 | 6.39 | 3.10 | 2.824 |
| Fresh water | L | 1.49 | 6.69 | 6.03 | 16.5 | 35.95 |
| Waste generated | Unit | — | — | — | — | — |
| Solid waste | kg | 0.0320 | 0.119 | 0.598 | 0.072 | 0.136 |

[a] 9.5-mm-thick oriented strandboard (OSB).
[b] 9.5-mm-thick softwood plywood (SE, Southeast; PNW, Pacific Northwest).
[c] 12.7-mm-thick cellulosic fiberboard (CF).
[d] 3.2-mm-thick hardboard (HB)/engineered wood siding and trim.

more fossil fuels were consumed during cellulosic fiberboard production. In addition, as one would expect, fossil nonrenewable energy consumption was consistent with global warming impacts (GWI) for all five wood panels.

Table 4 shows environmental impacts of producing 1 $m^2$ of wood panels. CPEC for wood panel production on a square meter basis varied slightly from 68.7 to 88.3 MJ/$m^2$ considering the range of the thicknesses for the wood panels. Given the change in units from a cubic to square meter, the tightening of the variability was expected because hardboard was by far the thinnest panel and thus, would benefit the most when considered on an area basis. As shown in Table 3, hardboard's primary energy consumption was nearly four times the amount on a volume basis compared with the other panel products. This difference was substantially decreased when shown on an area basis.

Table 5 shows environmental impacts of producing 1 $m^2$ of wood panels on a percentage basis. A couple of items stood out. First, there was a wide variation in the component of biomass energy of the CPEC of the wood panels. It ranged from 12.2% for cellulosic fiberboard to 64.0% for PNW softwood plywood. Secondly, as shown previously, fossil nonrenewable energy consumption was consistent with GWI for all five wood panels. The difference was that cellulosic fiberboard showed the greatest fossil nonrenewable energy consumption and thus the greatest GWI, not hardboard. As mentioned previously, this was primarily because cellulosic fiberboard production facilities can use low-quality wood for feedstock instead of as boiler fuel thus needing to consume more fossil fuels in their boilers (Bergman 2014a, 2015b).

As previously mentioned, previous LCA studies have been completed in the United States on softwood panel products. The original US LCI studies (Kline 2005; Wilson and Sakimoto 2005) were updated as part of a larger research effort into LCA. Puettmann et al (2013a, 2013b, 2013c) reported CPEC of 90.7, 58.9, and 47.5 MJ/$m^2$, with biomass energy percentage of 41.9%, 59.0%, and 56.0% for SE US OSB, SE US softwood plywood, and PNW US softwood plywood, respectively. In addition, GWI of 2.62, 1.27, and 0.98 kg $CO_2$-eq/$m^2$ were estimated, respectively. Canadian LCIA results reported CPEC for OSB and plywood of 43.8 and 24.2 MJ/$m^2$, respectively, with biomass energy percentage of 54.6%

Table 5. Life cycle impacts of 1 $m^2$, wood panels, US average, gate-to-gate (mass allocation), percentage basis.

| Impact category | Percentage | OSB[a] | SE[b] | PNW[b] | CF[c] | HB[d] |
|---|---|---|---|---|---|---|
| Global warming | (%) | 51.4 | 49.6 | 32.1 | 100 | 64.5 |
| Acidification | (%) | 18.7 | 17.8 | 13.1 | 100 | 79.4 |
| Eutrophication | (%) | 13.9 | 7.9 | 7.0 | 81.9 | 100 |
| Ozone depletion | (%) | 2.2 | 0.4 | 0.4 | 46.5 | 100 |
| Smog | (%) | 9.7 | 7.7 | 6.9 | 100 | 90.8 |
| Primary energy consumption | | | | | | |
| Nonrenewable, fossil | (%) | 56.0 | 55.6 | 37.0 | 100 | 70.6 |
| Nonrenewable, nuclear | (%) | 76.8 | 78.6 | 37.3 | 97 | 100 |
| Renewable, other | (%) | 13.1 | 7.5 | 37.4 | 100 | 17.4 |
| Renewable, biomass | (%) | 84.0 | 83.6 | 100 | 21.1 | 94.2 |
| Total primary energy | (%) | 83.8 | 83.2 | 77.8 | 86.1 | 100 |
| Material resources consumption (nonfuel) | | | | | | |
| Nonrenewable materials | (%) | 46.7 | 28.0 | 56.1 | 36.4 | 100 |
| Renewable materials | (%) | 70.3 | 100 | 90.4 | 43.8 | 39.9 |
| Fresh water | (%) | 4.1 | 18.6 | 16.8 | 45.9 | 100 |
| Waste generated | | | | | | |
| Solid waste | (%) | 5.4 | 19.9 | 100 | 12.0 | 22.7 |

[a] 9.5-mm-thick oriented strandboard (OSB).
[b] 9.5-mm-thick softwood plywood (SE, Southeast; PNW, Pacific Northwest).
[c] 12.7-mm-thick cellulosic fiberboard (CF).
[d] 3.2-mm-thick hardboard (HB)/engineered wood siding and trim.

and 60.1%, which was lower than the old and new US values. In addition to, GWI of 1.07 and 0.49 kg $CO_2$-eq/$m^2$ were estimated, respectively (ASMI 2012a, 2012b). Electricity consumed for the Canadian production of OSB and softwood plywood is dominated by hydropower. One possible explanation for the greater new US values especially for plywood is the greater use of emission control devices including baghouses and regenerative catalytic oxidizers. These are becoming more prevalent because of increased regulatory controls in the United States since the 2000s when Phase I survey data were collected.

The impact of carbon stored in the final product was compared with GWI for the five wood panel products. The results showed that the carbon content for OSB, SE plywood, and PNW plywood was greater than 100% compared with their respective GWI at 144%, 129%, and 177%, respectively. As for cellulosic fiberboard and hardboard, the wood panel carbon was 42% and 51% of their respective manufacturing GHG emissions. One reason for the large variation was that cellulosic fiberboard was able to consume raw materials of lower quality, whereas hardboard production consumed large amounts of electricity (654 kWh/$m^3$) especially during the refining process (Bergman 2014b, 2015b) compared with the other panel products. Of course, the type of in-place service drives how the individual wood panels are produced (Suchsland and Woodson 1986; USEPA 2002; Stark et al 2010).

There are a couple more things to consider. One, CPEC for wood panel production on a square meter basis varies slightly although wood panel thicknesses vary substantially. Wood panel thickness has less effect than the wood panel density. More specifically, one would assume thinner panels consumed less energy but the final density of the finished product has a more substantial role because the denser and thinner wood panels such as hardboard require the most energy. Secondly, the component of biomass energy of the CPEC of the wood panels varied widely. This is an indication of the wood fuel available on-site to produce thermal (process) energy for the various processes. For most wood panels, hog fuel, a mixture of residues generated during product production, is readily available except for cellulosic fiberboard production. However, what most wood panel products would consider hog fuel at their production facility to be burned in a boiler for thermal energy, a cellulosic fiberboard production facility could use as a feedstock.

Regardless, for cellulosic fiberboard production, its use of woody biomass for on-site energy is limited unless a large source of underutilized wood is available nearby. Expectedly, the trade-off for greater material use is that cellulosic fiberboard has the greatest GWI on a square meter basis because of their need to burn fossil fuels to generate the process energy required. Therefore, companies and other stakeholders have to decide if greater material use or lower GHG emissions are the most important outcome during product production. Of course, one thing not investigated was what would happen to the material if not used as feedstock. Most likely, it would end up in a landfill in the United States.

## CONCLUSION

This study summarizes four studies of the environmental impacts associated with gate-to-gate manufacturing of North American wood panel production. Densities and panel thicknesses have the greatest impacts on converting from a cubic meter to a square meter basis for the various life cycle impacts evaluated. In addition, using woody biomass energy for panel production decreases their impact on climate change. However, panel products with greater material use may lose out on the full benefit because of the requirement to use more fossil fuels to compensate. The release of GHG emissions is especially great when fossil fuels are consumed to generate steam (ie thermal energy) for the drying process. Using woody biomass instead of fossil fuels would lower the GWI of the various wood panel products produced.

The carbon stored in wood products can offset the manufacturing GHG emissions released to the atmosphere. In this study, the carbon stored in the wood panels substantially offset these GHG emissions and in most cases, the carbon stored was greater than the gate-to-gate manufacturing GHG emissions released during manufacturing.

The five panel products evaluated here are mostly not interchangeable. Thus, results for the various products should not be compared without considering the use of the panel product itself in service. Panel thickness varied among the various wood panel products, ranging from 3.18 to 12.7 mm. Therefore, LCIA results are more representative when shown by area with a given basis, as shown in this study, which corresponds with how the panel products are marketed for building in the United States.

## ACKNOWLEDGMENTS

Primary funding for the cellulosic fiberboard project was through a cooperative agreement between the USDA Forest Service Forest Products Laboratory and the North American Fiberboard Association (13-CO-11111137-017). FPInnovations provided additional funding. Funding for the hardboard and engineered wood siding and trim project was through a cooperative agreement between the USDA Forest Service Forest Products Laboratory and the Composite Panel Association (13-CO-11111137-014). We especially thank those companies and their employees that participated in the surveys to obtain primary production data.

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