Cradle-To-Gate Life Cycle Assessment of North American Hardboard and Engineered Wood Siding and Trim Production

Prepared for:

CPA – Composite Panel Association

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1 BACKGROUND

CORRIM, the Consortium for Research on Renewable Industrial Materials (www.corrim.org), has derived life-cycle inventory (LCI) data for nine major wood products and four wood production regions in the United States (US). The LCI data cover forest regeneration through to final product at the mill gate. CORRIM's LCI studies have included both structural and nonstructural wood products. This report focuses on the average North American production of hardboard and engineered wood siding and trim (EWST). Hardboard and EWST are in the same composite wood product category and in this report will be collectively be referred to as "hardboard".

This document develops the cradle-to-gate hardboard life-cycle assessment (LCA) and reports a life cycle impact assessment in using the previously published LCI data by Bergman (2015). Prior to Bergman's publications, no prior North American (NA) hardboard LCI had been documented. The LCI data developed for the manufacturing life-cycle stage will be contributed to the US LCI Database (https://www.lcacommons.gov/nrel/search).

The LCA can be used internally by the Composite Panel Association (CPA) and its members to explore potential process and parameter improvements and new conversion technologies along with the identification of environmental 'hotspots'. The LCA can also be used by LCA practitioners and building specifiers looking for green building products with documentation. It is formatted for inclusion into environmental footprint software such as the Athena Impact Estimator for Buildings (ASMI 2015) which is used for whole building LCAs. It can also be used as part of a whole building LCA in green building certification rating systems such as LEED v4, Green Globes, and the ICC-700 National Green Building Standard 2012 (http://awc.org/greenbuilding).

Treatment of biogenic carbon was based on the Norwegian Solid Wood Product Category Rule (Aasestad 2008) and the North American Product Category Rule (hereafter PCR) (FPInnovations 2015) to ensure comparability and consistency. The LCA is in conformance with the PCR (FPInnovations 2015) and ISO 14040/14044 standards (ISO 2006a, 2006b) for conducting LCAs. This report follows data and reporting requirements as outlined in the PCR and contains the required components for producing a NA Environmental Product Declaration (EPD) (ISO 2006c).

2 METHODS

2.1 Life-cycle assessment

Life-cycle assessment (LCA) has evolved as an internationally accepted method to analyze complex impacts and outputs of a product or process and the corresponding effects they might have on the environment. LCA is an objective process that identifies and quantifies energy and materials used and wastes released to the environment, assesses the impact of those energy and materials uses and releases on the environment, and evaluates opportunities for environmental improvement.

LCA studies can evaluate full product life cycles, referred to as “cradle to grave,” or incorporate only a portion of the products life cycle, referred to as “cradle to gate,” or “gate to gate.” This study can be categorized as a cradle to gate LCA and includes forestry operations through to the manufacturing of hardboard ready to be shipped from the mill gate.

As defined by the International Organization for Standardization (ISO 2006a), LCA is a multiphase process consisting of a 1) Goal and Scope Definition, 2) Life Cycle Inventory (LCI), 3) Life Cycle Impact Assessment (LCIA), and 4) Interpretation (Figure 1). These steps are interconnected and their outcomes are based on goals and purposes of a particular study.

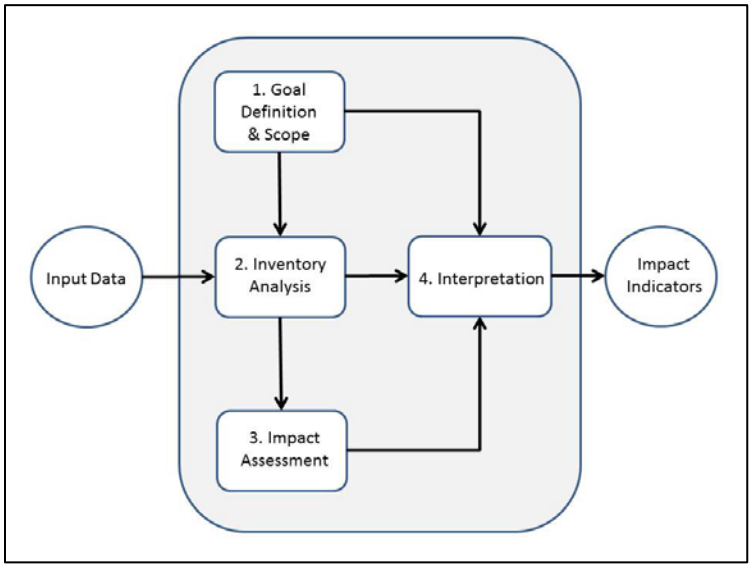

Figure 1. Steps involved in a life-cycle assessment.

During goal and scope definition, the functional unit, system boundaries, any assumptions and study limitations, method of allocation, and the impact categories that will be used are identified.

The key component of the LCA is the LCI which is an objective, data-based process of quantifying energy and raw material inputs, air emissions, waterborne effluents, solid waste, and other environmental releases occurring within the system boundaries. It is this information that provides a quantitative basis for reporting on wood products environmental performance and its comparative impacts relative to alternative products.

2.2 Life cycle impact assessment

The LCIA process groups the effects of environmental releases identified in the LCI into impact categories such as global warming potential (GWP), acidification, carcinogenics, respiratory effects, eutrophication, ozone depletion, ecotoxicity, and smog (Figure 2). A number of impact assessment methods are available. For assessing the environmental impacts of the hardboard production, the TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) impact method was used. TRACI is a midpoint oriented LCIA methodology developed by the U.S. Environmental Protection Agency specifically for the United States using input parameters consistent with U.S. locations (Bare 2011). TRACI is available through the SimaPro LCA software used for modeling hardboard (PRé Consultants 2016).

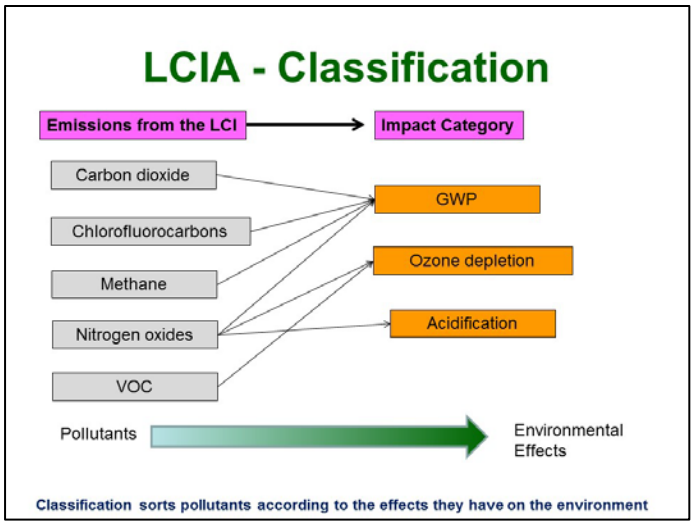

Figure 2 Classification of LCI emissions into impact categories

2.3 Life cycle interpretation

The life-cycle interpretation phase of the LCA uses the findings of either the LCI or the LCIA, or both, to reach conclusions and recommendations about the defined goal and scope. This final step in an LCA involves an investigation of significant environmental aspects (e.g., energy use, greenhouse gases), their contributions to the indicators under consideration, and determination of which unit processes in the system they emanate from. For example, if the results of a LCIA indicate a particularly high value for the GWP, the analyst could refer back to the inventory to determine which environmental flows are contributing to the high value, and which unit processes those outputs are coming from. This is also used as a form of quality control in which case the results could be used to refine the scope definition to focus on the more important unit processes. This step also supports arriving at more certain conclusions and supportable recommendations.

3 Description of Product

Hardboard (Figures 3 and 4) is a non-structural panel product developed to utilize industrial wood residue. These woody biomass residues were historically burned for energy or sent to landfill to dispose of them as waste material. Over the last several decades, hardboard has evolved into a highly engineered product designed to meet specific end-use requirements. Final products made from hardboard commonly called "dealer board" include case-goods, paneling and pegboard (Figure 5). The production of hardboard falls into the North American Industry Classification System (NAICS) Code 321219—reconstituted wood products, which include other wood composite products such as cellulosic fiberboard, medium density fiberboard, particleboard, and oriented strandboard (USCB 2012). Hardboards are composite panels designed and manufactured to perform in applications with the appearance of traditional wood. In addition, all hardboard plants follow the "Eco-Certified Composite (ECC) sustainability standard" (www.compositepanel.org/cpa-green/go-ecc-green.html) (CPA 2012a). The ECC is a voluntary industry standard developed by the CPA for manufacturers of wood or agri-fiber based composite panels. The standard focuses on LCI and other verifiable environmental practices and highlights the responsible use of natural resources by composite panel manufacturers.

Figure 3. Hardboard/EWST (top view).

Figure 4. Hardboard/EWST (side view).

Hardboard manufacture involves breaking down wood into its basic fibers then placing the wood back together with the fibers repositioned along with a resin system to form hard panels that have their own set of separate and distinct properties. Manufacturing hardboard in NA currently uses either a wet or dry production processes to create high-density wood composition panels (CPA 2012b, c)[1]. Both wet and dry processes use a thermomechanical process to reduce the wood chips or raw material to individual fibers. Resin and additives are added to the fibers 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

[1] Previously, a semidry process was explored as a hybrid process to lower resin and water usage while maintaining more of the properties found in wet-process hardboard (Myers 1986). However, the semidry process did not offer any manufacturing advantages or panel performance advantages so the industry discontinued its production (Heroux 2015a).

properties (Baird and Schwartz 1952; Lewis 1965; Suchsland and Woodson 1986). In this study, oil tempering was included within the system boundaries, however no specialty coatings were included within the system boundary. Density for the final products ranges from 800 to 1,100 kg/m^3 (Figure 5) (USEPA 2002; González-García et al. 2009; Stark et al. 2010).

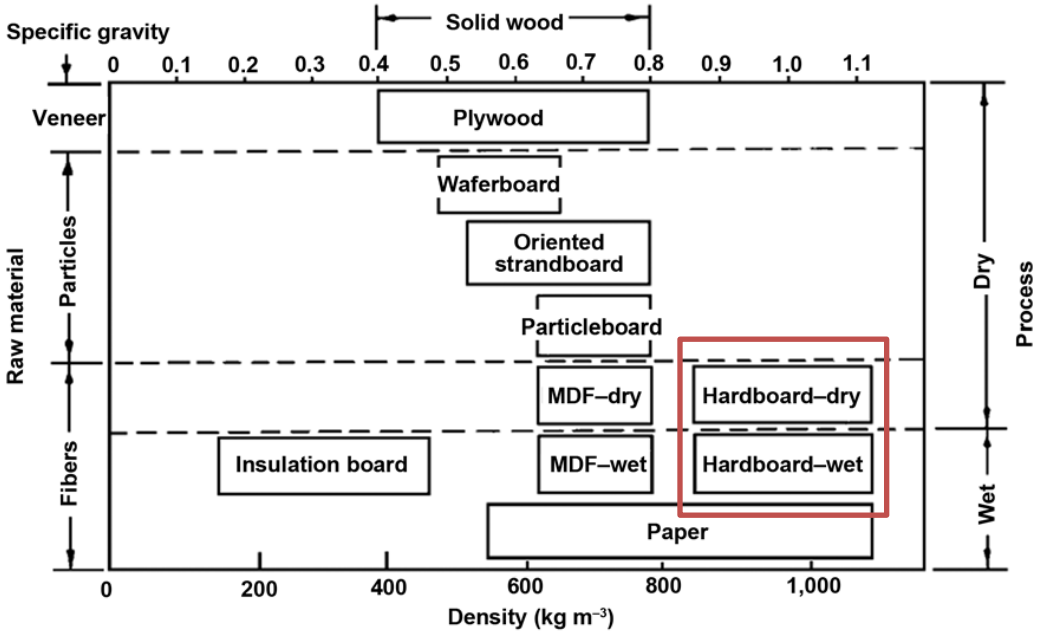

Figure 5. Classification of wood composite panels by particle size, density, and process (Suchsland and Woodson 1986).

The present study does not make a distinction between hardboard and EWST except for the standards used to produce these products. North American hardboard is classified by the following standards: 1) Basic Hardboard - ANSI A135.4-2012 (CPA 2012b) and 2) Prefinished Hardboard Paneling-ANSI A135.5-2012 (CPA 2012c). North American EWST is classified by the following standards: 1) Engineered Wood Siding-ANSI A135.6-2012 (CPA 2012d) and 2) Engineered Wood Trim-ANSI A135.7-2012 (CPA 2012e). Various uses and applications for hardboard and EWST include 1) furniture components, 2) wall paneling, 3) moulded door skins, 4) underlayment, and 5) perforated boards.

3.1 Study goals and scope

The goal of the present study was to determine energy and material inputs and outputs associated with the production of hardboard representing average manufacturing practices in NA. The data were obtained by surveying manufacturers in the U.S. and Canada. Surveys were consistent with CORRIM protocols for performing LCI's of wood products, follow ISO14040/140444 standards for conducting LCA (ISO 2006b, ISO 2006c), and meet the requirements of the PCR (FPInnovations 2015).

The scope of this study was to develop an LCA for the production of hardboard including from a variety of wood residues using practices and technology common to North American forestry

and manufacturing sectors. It covers the impacts in terms of input materials, fuels, and electricity through to the outputs of product, co- products, and emissions. The wet- and dry-process hardboard were analyzed as a combined single unit process. Cradle-to-gate LCI data on material flows, energy type and use, emissions to air and water, solid waste production, and water impacts are reported on a unit volume basis of 1 m^3 (Bergman 2015). LCIA results are reported for cradle to gate primary energy use, non-renewable and renewable resources, water use, and impact categories as required in the PCR.

3.2 Intended audience

The primary audience for the LCA report includes the North American hardboard and EWST manufacturers, and other LCA practitioners.

3.3 Comparative assertions

The report does not include product use and end of life phases which are required for comparative assertions relative to substitute products. If future comparative studies are intended and will be disclosed to the public, the LCA boundary would need to be expanded to include the use and end of life phases consistent with the ISO 14040/44:2006 (ISO 2006a) guidelines and principles and for compliance with the PCR (FPInnovations 2015).[2]

3.4 Functional and declared unit

In accordance with the PCR (FPInnovations 2015), the declared unit for hardboard is one cubic meter (1.0 m^3). A declared unit is used in instances where the function and the reference scenario for the whole life cycle of a wood product cannot be stated (FPInnovations 2015). For conversion of units from the U.S. industry measure, 1,000 square feet (1.0 MSF) at 0.125-inch basis is equal to 0.295 m^3. All input and output data were allocated to the declared unit based on the mass of products and co-products in accordance with ISO 14044 (ISO 2006b). As the analysis does not take the declared unit to the stage of being an installed building product, no service life is assigned.

3.5 System boundaries

The system boundary begins with regeneration in the forest and ends with hardboard (Figure 6). The forest resources system boundary (A1) may include site preparation and planting seedlings, forest management which may include fertilization and thinning, harvesting, transportation of logs to the primary breakdown facility, wood residue production during lumber manufacturing processes, transportation to the hardboard facility, and hardboard production (6). Seedlings and the fertilizer and electricity it took to grow trees were considered as inputs to the system boundary. The hardboard production complex (A3) was modeled as a single process representing all the steps necessary to make hardboard for both the wet and dry processes. Transportation (A2) of extracted resources to primary wood processing facilities and feedstocks to hardboard production are also included in the system boundary.

[2] If the LCA is used to develop an Environmental Product Declaration (EPD), internal and/or external critical review would be required.

This study found that wood residue inputs for NA average hardboard production are sourced from several forms of woody biomass including roundwood and co-products from various wood manufacturing processes. Roundwood materials include upstream forestry operations as part of their processes. Co-products from wood manufacturing carry the environmental burdens from upstream forestry processes plus any manufacturing steps that occurred prior to their delivery to the hardboard facility.

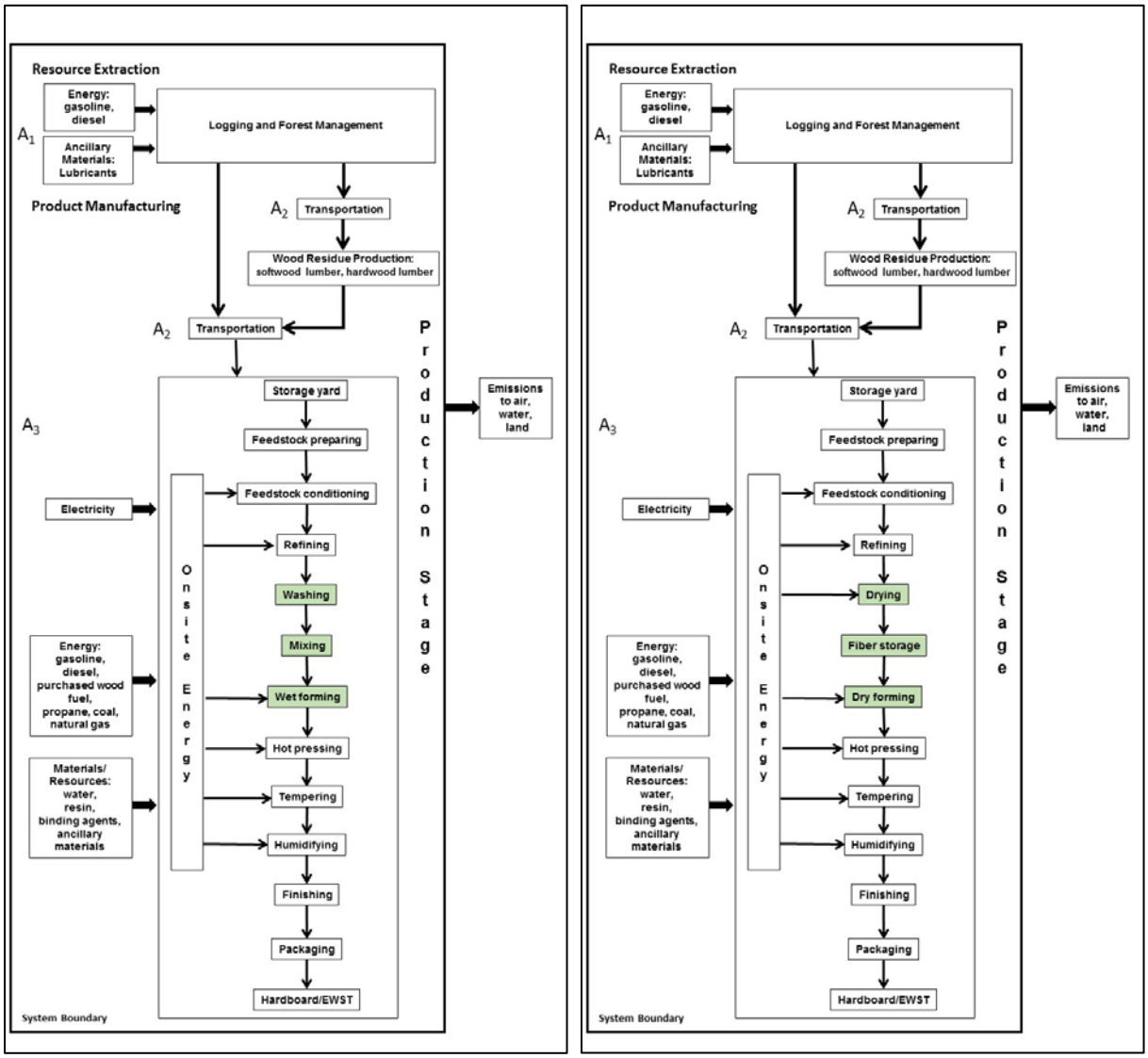

Figure 6. System boundary and process flow for cradle-to-gate production of hardboard for both wet and dry forming processes.

3.5.1 LCI processes

3.5.1.1 Forestry Operations.

Forestry operations vary regionally (Johnson et al. 2005; Oneil et al. 2010; ASMI 2012) but typically include some combination of growing seedlings, natural regeneration, site preparation, planting, thinning, fertilization (where applicable), and final harvest. Harvesting included felling, skidding, processing, and loading for both commercial thinning and final harvest operations. For NE-NC US forests and Canadian hardwood forests, reforestation occurs using natural regeneration which does not require inputs from human-related activities (i.e., the technosphere) for seedlings, site preparation, planting and pre-commercial thinning (Figure 6), whereas these steps were included for regeneration of softwood forests in the SE, PNW, and NE-NC regions. Weighted average allocation to different processes takes into account inherent differences in site productivity, yield, forest management activities, and energy usage by different kinds of logging equipment. Allocations for forest resource LCI data inputs were 30.7 percent from the Southeast (SE) softwood and hardwood forests, and 16.9 percent from Pacific Northwest (PNW) softwood forests (Johnson et al 2005), 32.4 percent from the Northeast North-Central hardwood and softwood (NE-NC) US forests (Oneil et al. 2010) and 19.9 percent from Canadian hardwood forests (ASMI 2012). Inputs to the forest resources management LCI include seed, electricity used during greenhouse operations, fertilizer used during seedling production and stand growth, and the fuel and lubricants needed to power and maintain equipment for thinning and harvest operations. The primary output product is a log destined for sawn lumber. The co-product, non-merchantable (logging) slash, is generally left on site. Slash disposal was not modeled as it was assumed to decay in-situ. Details of all forestry operations processes are provided in Johnson et al. 2005 and Oneil et al. 2010 for the U.S. and ASMI 2012 for Canada. A summary of the energy use and fuel consumption for the forest operations by region, along with the weighted average values used in hardboard production are provided in Table 2.

Table 1. Fuel consumption for regional forest resource management processes (regeneration, thinning, and harvest).

	Unit	Fuel Consumption per m^3				
		Canadian hardwoods	PNW softwoods	NE-NC hardwoods and softwoods	SE softwoods and hardwoods	Weighted Average
Seedling, Site Prep, Plant, Pre-commercial Thinning						
Diesel and gasoline	L	0	0.088	0	0.515	**0.191**
Lubricants	L	0	0.002	0	0.009	**0.004**
Electricity	kWh	0	0.107	0	0.455	**0.179**
Commercial Thinning and Final Harvest						
Diesel	L	4.83	2.85	4.27	2.93	**3.73**
Lubricants	L	0.132	0.051	0.077	0.05	**0.075**
Electricity	kWh	0.264	0.264	0	0	**0.097**
Total Forest Extraction Process						
Gasoline and Diesel	L	4.83	2.94	4.27	3.45	**3.92**
Lubricants	L	0.132	0.053	0.077	0.059	**0.079**
Electricity	kWh	0.264	0.371	0	0.455	**0.277**

[1] PNW: Pacific Northwestern United States.
[2] NE-NC: Northeastern/North Central United States.
[3] SE: Southeastern United States.

3.5.1.2 Wood residue.

Most wood residues come from co-products generated during lumber production. Wood residue attributes vary across the major production centers of North America. Residues include softwoods from the PNW and SE, hardwoods from Canada, and softwoods and hardwoods from the SE and NE-NC (Table 2) (Milota 2015a,b; Bergman and Bowe 2008; Bergman and Bowe 2010; Bergman and Bowe 2012; ASMI 2012). Chips, a co-product from sawmill operations, represent the largest wood residue input at 69 percent (584 kg, oven dry) followed by roundwood and green sawdust at 20 and 11 percent, respectively. The highest quantity of wood residues consumed during the hardboard manufacturing process was from the NE-NC region at 274 oven dry (OD) kg followed by residues from the SE region at 259 OD kg. Canada provided about 20 percent of the wood residues consumed. All feedstock produced in a particular region were utilized within the same region.

Table 2 Wood residue type and source for input for hardboard production, North America average.

Regional allocation (%)	Wood residue type	Mass of residue kg/m^3	Residue allocation (%)
	Canada (CN)		
20	Roundwood, hardwood, Canada	168	100
20	TOTAL	168	100
	Pacific Northwest U.S.		
11	Sawdust, softwood, green	91	64
6	Chips, softwood, green	51	36
17	TOTAL	142	100
	Northeast-North central, U.S.		
30	Chips, hardwood, green	254	93
2	Chips, softwood, green	19	7
32	TOTAL	274	100
	Southeast, U.S.		
26	Chips, hardwood, green	215	83
5	Chips, softwood, green	44	17
31	TOTAL	259	100
	Canada	168	**20**
	Pacific Northwest	143	**17**
	Northeast-North central	274	**32**
	Southeast	259	**31**
	TOTAL North American	844	**100**

3.5.1.3 Resource transport

Wood raw materials are delivered to the mill by truck. The wood raw material consists of roundwood, green chips and green sawdust of various moisture contents. The terms wood and pulp fibers are used interchangeably in the present study (Lampert 1967; Suchsland and Woodson 1986; USEPA 2002; Stark et al. 2010; ASTM International 2012). The moisture

content of the residue can range from 35 to 100% on an oven-dry weight-basis. Based on mill surveys, the average haul distance for feedstock along with the components of the resin system is shown in Table 3.

Table 3 Weighted average delivery distance (one-way) by truck for materials to hardboard mill, North American average

Material delivered to mill	Distance	
	km	miles
Roundwood	77	48
Chips, green	70	44
Sawdust, green	0.2	0.1
Phenol-formaldehyde resin	376	234
Alum	236	146
Paraffin emulsion (Wax)	591	367
Linseed oil	306	190
Slack wax	1,304	810
Zinc borate	161	100
Wood fuel, purchased	70	44

Once feedstocks are at the mill, the wood fibers may enter a wet process or a dry process to form boards from the wood fibers leaving the refining process (Figure 6). Over 90% of hardboard production occurs through the wet process. Once hot pressing is complete, the boards from the wet and dry process continue on a similar process starting at the cooling and tempering step.

3.5.1.4 Wood Product Manufacturing.

Eleven main unit processes were identified in manufacturing wet- and dry-process hardboard (Table 4) (Suchsland and Woodson 1986; Bergman 2014). There are 3 differences in these steps as noted in Table 4.

Table 4 Process steps for wet and dry production of hardboard. *Italicized* steps are steps that are different between the two processes.

Process Step	Wet Process	Dry Process
1	Resource Transportation	Resource Transportation
2	Yard Storage	Yard Storage
3	Feedstock Preparation	Feedstock Preparation
4	Refining	Refining
5	*Washing*	*Drying*
6	*Mixing*	*Fiber Storage*
7	*Wet Forming*	*Dry Forming*
8	Hot Pressing	Hot Pressing
9	Tempering	Tempering
10	Humidifying	Humidifying
11	Finishing	Finishing

The main difference involves the conveying medium. The wet process is similar to producing cellulosic fiberboard (Suchsland and Woodson 1986), which has water as the conveying medium. For dry-process air is the conveying medium. Both processes require additions of phenol-formaldehyde (PF) resins and additives (i.e. resin system) for bonding. All differences were included in the analysis to show the overall impact. For example, dry-process hardboard consumed more PF resin per production unit but consumed less additives than the wet-process. Water and process energy consumption were similar between all plants with one wet-process plant notably consuming more on a per production unit basis. The dry- and wet-processes were merged into a single system based on weighted average plant production to develop the LCI. All environmental outputs (emissions) and energy consumed were assigned on a mass basis and reported based on a single hardboard production system.

Table 5 Hardboard/engineered wood siding and trim process board forming stages

Wet and Dry Process			
Storage yard	Upon arrival at the storage yard, all wood raw materials were weight-scaled and moisture levels determined. Log stackers or front-end loaders were used to transport roundwood and chips from the storage yard to the mill. Inputs included roundwood with bark, green chips, green sawdust, fuel, and lubricants. Outputs included roundwood with bark, green chips, green sawdust, and emissions from burning fossil fuels used by the storage yard machines.		
Feedstock conditioning	The wood raw material arrives at the facilities in various forms (roundwood, chips, and sawdust) and thus requires preparation before refining to generate a homogeneous form. If roundwood is used, onsite wood chipping is necessary. Green chips are screened to remove over-sized chips so they may be re-chipped and then washed to remove dirt and other foreign substances. Steam digesters and steaming screws are typically used for conditioning chip and other wood raw material. Inputs include wood raw material, water, steam, and electricity. Outputs from this process include chips.		
Refining	The refining process mechanically reduces the wood fibers using pressurized disk refiners that shear the wood and separate the fibers from the lignin. Steam is used to soften the material. Refining is an energy-intensive process with an average energy use ranging from 250 to 380 kWh/tonne for wet-process hardboard and 125 to 250 kWh/tonne for dry-process hardboard stock produced (Suchsland and Woodson 1986). Heating conditions of the wood raw material depend on wood species with hardwoods requiring less time than softwoods (Suchsland and Woodson 1986). Inputs include chips, sawdust, electricity, and heat. Outputs include pulp fiber and water vapor. In addition, for dry-process hardboard, wax may be added at this stage (USEPA 2002).		
Wet Process		**Dry Process**	
Washing	The pulp fibers are washed to remove wood sugars (i.e., molasses). In addition, washing removes dirt and other foreign material. Inputs are pulp and water and outputs are pulp and water along with wood sugar and solid waste.	**Drying**	Before drying, slack wax is added in the refining stages while the other additives of the resin system are added commonly through a blowline. This injection of additives produces wet resinated fibers. The wet resinated fibers are dried from 50 to approximately 20% MC via tube dryers, then the dried resinated fibers are conveyed to dry storage. There may be secondary tube dryers along the primary tube dryers to dry the boards to roughly 5% MC. The tube dryers are typically direct-heated from burning wood and other fuels. Drying emissions are sent to regenerative thermal oxidizers to destroy volatile organic compounds emitted during the drying process. Inputs include wet fibers, resins, additives, combustion exhaust, fuel, and electricity while outputs include dry resinated fibers, volatile air emissions, and wet cool air.
Mixing	During mechanical mixing water is added to the pulp fibers along with phenol-formaldehyde (PF) resin and additives for bonding the pulp fibers. Adding the additional water creates a slurry. Lignin aids the resin system in bonding the pulp fibers. Inputs include pulp, water, and the resin system and the output is a slurry.	**Fiber storage**	During storage, the dry resinated fibers are prepared and staged for dry forming. Enough dry resinated fibers are stored to ensure the next stage, dry forming can be done at full speed.

Wet forming and pressing	The low-consistency slurry, about 2% fiber, is pumped to board-forming machines where the slurry is metered unto a wire screen. Gravity and vacuum applied gradually to the bottom of the wire removes the water from the mat being produced. After leaving the wire at about 25% solid fiber, the fiber mat is cut to length and trimmed by high-pressure water jets. The board is wet-pressed using continuous rollers at room temperature to remove additional water while pressing the board to its final thickness plus a shrinkage allowance for drying. Most of the collected water is recycled. Inputs include pulp, water, and electricity and outputs include a fiber mat, trim residue, water, and steam.	**Dry forming and pressing**	Dry forming is a batch process. The dry resinated fibers are conveyed to the forming machine where they are pre-pressed into a mat and trimmed. The inputs include dry resinated fibers and electricity and the outputs include a dry fiber mat and trim residue.
Hot pressing/ Drying	Board drying is a continuous energy-intensive process to help set and cure the resin. The boards of about 65 to 75% moisture are conveyed on chain-driven rollers into a heated-enclosure broken into zones where the steam-heated presses remove most of the remaining water in vapor form (i.e., steam). The zones are at different temperatures and air flows. In total, about two tonnes of water are removed per tonne of dry board. The press cycles are dependent upon press temperatures, board thickness, board density, and wood species and thus vary from mill to mill. All wet process hardboards are surfaced on one side and are called S1S boards. Inputs include wet boards, combustion air, electricity, and combustion gases from burning wood fuel and outputs include dry boards, steam, fossil and biogenic carbon dioxide, and volatile organic compounds (VOCs).	**Hot Pressing**	Board drying is a batch process. The mat enters a hot multi-opening press that activates the PF resin and bonds the fibers in the mat into the board. The presses are indirectly heated from boiler steam. The board leaves the press as S2S (smooth on both sides) hardboard. Inputs include dry fiber mat, indirect steam, and electricity while outputs include dry hot boards, steam, and volatile organic compounds.
Wet and Dry Process			
Cooling/ tempering	Before tempering, the dry hot boards are cooled and linseed oil is sometimes added. In the wet-process, the cooled boards are dried further to aid in dimensional stability and physical properties (USEPA 2002). The tempering process can be performed with direct or indirect heating. Regardless of the process, all boards are humidified to the expected equilibrium moisture content to complete the tempering process. Inputs include the dry hot boards, heat, linseed oil, and moisture and outputs include the unfinished hardboard.		
Finishing	Trimming reduces the unfinished hardboard to final standard dimensions, typically 1.22 m by 2.44 m. Input includes unfinished hardboard and output includes the final hardboard product, culled boards, and wood dust. Culled boards are boards that fail to pass a quality control inspection and are ground up for wood fuel. For this study, the hardboard was not coated.		
Packaging	Finished hardboard is packaged for transport using wooden runners. Inputs include final product (hardboard) and packaging material like plastic wrapping and outputs including packaged hardboard		

3.5.1.5 Packaging

Packing materials represent less than 1% of the cumulative mass of the model flow. The material list was developed from mill survey data. The wooden runners make up the bulk of this mass, representing 75.6% of the total packaging material The cardboard strap protectors, wrapping material, plastic strapping, and steel strapping made up 15.4, 5.4, 3.4, and 0.2% of the packaging by mass, respectively.

Table 6 Packaging

Material	Value	Unit	Percent
Wrapping Material – HDPE and LDPE laminated paper	0.494	kg	5.4
PET Strapping	0.312	kg	3.4
Cardboard strap protectors	1.421	kg	15.4
Steel strapping	0.018	kg	0.2
Wooden runners	6.974	kg	75.6
Total	9.219	kg	100

3.5.1.6 Energy sources

Energy sources consumed onsite were derived from onsite and off-site sources. Onsite sources include process (thermal) energy used at the plant that was provided by burning a mix of natural gas, residual oil, and purchased and self-generated wood fuel. Thermal energy was commonly produced in the form of steam and then used in the conditioning, refining, and drying unit processes. Outputs from generating thermal energy included steam from the boilers, combustion gases from the drying process, solid waste (wood ash), and CO_2 (biomass and fossil). Off-site sources include grid electricity, which released its emissions off-site. Both onsite and offsite production emissions were reported as part of the LCI. Table 6 shows the electrical grid composition for the North American production of hardboard. Coal (51.8%) and nuclear (27.0%) power comprises most of the grid when manufacturing hardboard. Outputs included electricity

and emissions primarily of fossil CO_2.

Table 7 Percentage of energy source for electricity for producing North American hardboard

Energy source	Canada-Nova Scotia[a] (%)	NWPP[b] (%)	MRO[c] (%)	SRVC[d] (%)	North American composite grid (%)
Natural gas	4.2	14.3	3.3	11.7	10.2
Coal	84.0	31.3	65.8	45.7	51.8
Oil	4.9	0.3	0.4	0.5	1.2
Nuclear	0.0	3.4	14.4	38.2	27.0
Hydro	3.7	43.6	5.5	1.5	6.4
Wind	0.6	4.8	8.8	0.0	1.1
Biomass	2.7	1.2	1.5	2.0	2.0
Miscellaneous	0.0	1.0	0.3	0.3	0.3
Total	100	100	100	100	100

[a] Grid composition was developed from Ecoinvent high-voltage grid for Quebec.
[b] NWPP is the electrical grid comprised of Washington, Oregon, Idaho, Utah, most of Montana (less NROW), Wyoming (less RMPA), Nevada (less AZNM) and northern parts of California, Arizona, and New Mexico.
[c] MRO is the electrical grid comprised of Manitoba, Minnesota, Nebraska, North Dakota, Saskatchewan and parts of Illinois, Michigan, South Dakota and Wisconsin.
[d] SRVC is the electric grid comprised of North and South Carolina and most of Virginia (less southwest Virginia).

3.5.1.7 Energy Inputs

Onsite energy for the production of hardboard comes from electricity, woody biomass, natural gas, and residual fuel oil. Woody biomass sources include onsite generated and purchased wood fuels. Other fuels such as diesel, liquid propane gas (LPG), and gasoline are used to operate transport equipment within the mill. The electricity is used to operate equipment within the plant, including conveyors, refiners, fan motors, hydraulic press motors, high-pressure water jets, rollers, and emission control systems. Electricity is used throughout the process. The fuels for equipment are used for loaders and forklifts. Natural gas, residual fuel oil, and wood fuels are used to heat refiners, presses, and dryers.

Self-generated wood fuel is the primary fuel used in the hardboard manufacturing process at 318 OD kg per cubic meter of hardboard. This fuel is used for providing process heat for digesting, refining, drying boards, and heating steam or oil for hot rolling (Table 7). The second largest fuel source used onsite is purchased wood fuel. Natural gas is primarily used for drying boards through direct firing. Steam is produced by burning wood fuel along with residual fuel oil in a boiler to generate thermal energy. The total fuel use for process heat is 13.6 GJ/m^3 (3.82 million Btu/MSF) of which 93.1% is generated through the combustion of wood fuel (Table 8), 3.7% from residual fuel oil, and the other 3.2% from natural gas.

Table 8 Heat inputs per 1 m^3 hardboard, North American average

Fuel	Unit	Unit/m^3	HHV (MJ/kg)	MJ/m^3 of hardboard	% of total energy
Wood fuel – self-generated	kg	318	20.9	6,655	48.8
Wood fuel – purchased	kg	290	20.9	6,051	44.3
Residual fuel oil	kg	11.8	43.41	511	3.7
Natural gas[a]	m^3	7.9	54.41	431	3.2
Total Heat	MJ	-	-	13,647	100

[a] Density of natural gas 0.70 kg/m^3

CORRIM recently gathered U.S. boiler data from major wood producing facilities for on-site energy generation (Table 8) (Puettmann and Milota 2015). Regional differences in the United States were minor and therefore did not warrant developing separate boilers based on geographical regions. The CORRIM wood boiler process was used to model steam production from wood fuel. Both self-generated wood fuel and purchased wood fuel were used as inputs into the boiler for hardboard manufacturing. The wood-based fuel mix was 52.4 percent bark, bag house dust, culled boards, sander dust, and dry sawdust (self-generated) and 47.6 percent green chips and sawdust (purchased). Table 8 lists the wood boiler process inputs and outputs for manufacturing North American hardboard. The wood boiler profile is a composite process from the wood products industry

Table 9 CORRIM Wood Boiler used in the production of hardboard (Puettmann and Milota 2015).

INPUTS/OUTPUTS			
Inputs – Materials and Fuels		**Value**	**Unit**
Self-generated wood fuel		0.524	kg
Purchased wood fuel		0.476	kg
Transport, combination truck, diesel powered/US		1.38E-03	tkm
Diesel, combusted in industrial equipment/US		8.05E-04	L
Gasoline, combusted in equipment/US		3.96E-05	L
Liquefied petroleum gas, combusted in industrial boiler/US		1.21E-05	L
Lubricants		1.91E-05	L
Engine oil		2.22E-05	L
Hydraulic oil		0.00E+00	L
Antifreeze		4.81E-07	L
Ethylene glycol, at plant/RNA		1.07E-06	kg
Solvents[3]		7.17E-07	kg
Water Treatment		1.23E-04	kg
Boiler streamline treatment		3.67E-06	kg
Urea, as N, at regional storehouse/RER U		3.15E-03	kg
Disposal, ash, to unspecified landfill/kg/RNA		7.59E-03	kg
Disposal, solid waste, unspecified, to unspecified landfill/kg/RNA		7.26E-06	kg
Disposal, metal, to recycling/kg/RNA		3.96E-08	kg
Composite grid, North American		8.20E-02	kWh
Natural gas, combusted in industrial boiler/US		1.38E-03	m^3
Inputs - Water		**Value**	**Unit/kg**
Water, process, surface		3.10E-01	kg
Water, process, well		2.40E-01	kg
Water, municipal, process, surface		7.90E-01	kg
Water, municipal, process, well		2.40E-01	kg
Outputs – Products and Co-Products		**Value**	**Unit/kg**
CORRIM Wood Combusted, at boiler, at mill, kg, RNA		1.00E+00	kg
CORRIM Wood ash, at boiler, at mill, kg, RNA		2.00E-02	kg
Outputs - Emissions to air		**Value**	**Unit/kg**
Acetaldehyde		1.05E-06	kg
Acrolein		8.07E-07	kg
Benzene		1.69E-07	kg
Carbon monoxide, biogenic		3.23E-03	kg
Carbon dioxide, biogenic		1.76E+00	kg
Wood (dust)		5.62E-04	kg
Formaldehyde		1.26E-05	kg
HAPs		6.27E-06	kg
Hydrogen chloride		1.17E-06	kg
Lead		1.75E-07	kg
Mercury		1.83E-09	kg
Methane, biogenic		2.23E-05	kg
Methanol		7.95E-06	kg
Nitrogen oxides		1.10E-03	kg
Particulates, < 10 um		4.71E-04	kg
Particulates, < 2.5 um		1.39E-04	kg
Phenol		6.21E-07	kg

[3] Solvents may contain substances listed on the US Environmental Agency (EPA) Toxics Release Inventory. US Environmental Protection Agency, Toxics Release Inventory. http://www.epa.gov/toxics-release-inventory-tri-program/tri-listed-chemicals. Accessed January 2016

Propanal		5.14E-08	kg
Sulfur dioxide		7.71E-05	kg
VOC, volatile organic compounds		8.76E-04	kg
Dinitrogen monoxide		2.93E-06	kg
Naphthalene		5.77E-08	kg
Other Organic		2.11E-07	kg
Outputs - Emissions to water		**Value**	**Unit/kg**
Suspended solids, unspecified		8.35E-07	kg
BOD5, Biological Oxygen Demand		2.10E-06	kg

3.6 Cut Off Rules

According to the PCR, if the mass/energy of a flow is less 1% of the cumulative mass/energy of the model flow 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 (HAPS) specific to their wood products manufacturing process. Under Title III of the Clean Air Act Amendments of 1990, the EPA has designated HAPs that wood products facilities are required to report as surrogates for all HAPs. These HAPS are methanol, acetaldehyde, formaldehyde, propionaldehyde (propanal), acrolein, and phenol. All HAPS are included in the LCI, no cut off rules apply. If applicable to the wood product, HAPS are reported in Table 15 and would be included in the impact assessment. Table 15 shows all air emission to the 10^{-4} to simplify and report on the dominant releases by mass. There were no cut-offs used in the impact assessment therefore a complete list of all air emissions (smaller than 10^{-4}) is located in Appendix B of this report**.**

4 Data sourcing and averaging

The LCA for hardboard contains three life cycle stages: 1) Forest management and harvesting, 2) Wood residue production, and 3) Hardboard production. Primary and secondary data were used in all life cycle stages. This section provides a brief description of the primary and secondary data sources used to complete the LCA.

4.1 Primary and secondary data sources

Primary data on hardboard manufacturing was collected from mills in North America (n=4). Primary mill data were collected through a survey questionnaire mailed to hardboard plants (Bergman 2015) This survey requested from manufacturers inputs on raw materials (including fuels) and product and byproduct outputs and onsite emissions to water and air as well as solid waste generation and disposal methods for the 2012 production year. The participating facilities also provided information and data on the use of fuels, additives, energy consumption, electricity use, and ancillary inputs (e.g. lubricants, oils, greases, packaging, paints, etc.). Secondary data, such as pre-mill gate processes (e.g., forestry operations and wood residue production) were from peer-reviewed literature per CORRIM guidelines (CORRIM 2014). Material and energy balances were calculated from primary and secondary data (NREL 2012). These data were modeled using the software package SimaPro 8+ (Pré Consultants 2016).

Forest management and harvesting LCI data used in this study were derived from earlier studies on forest operations in the PNW (Canada), SE, and NE-NC U.S. regions and Canada (Johnson et al. 2005, Oneil et al. 2010, ASMI 2012). The data included a weighted average of various harvesting and forest management methods used in each forest types. The forestry systems from each of these regions were a weighted to represent a common forestry system for hardboard production (Table 11).

Wood residue production data used in this study were derived from CORRIM data using SE hardwood and softwood lumber (Bergman and Bowe 2012, Milota 2015b), PNW softwood lumber production (Milota 2015a), and NE-NC hardwood and softwood lumber (Bergman and Bowe 2008, 2010) (Table 10).

Feedstock transportation for hardboard mills was by road. The LCA incorporated an appropriate diesel tractor-trailer LCI from the US LCI database (https://www.lcacommons.gov/nrel/) based on transportation distances and mass of feedstock (logs or residue) for each mill location. Table 9 list the secondary LCI data sources used in this LCA study.

Table 10 Secondary LCI data sources used.

Process	LCI data Source	Publication date
Diesel truck	USLCI data for "Transport, combination truck, diesel powered/US"	2008
Electricity	USLCI data for "Electricity, at Grid, NPCC, 2008/RNA U"	2008
Forestry and Harvesting	CORRIM forestry operations data for: NE-NC hardwoods NE-NC softwoods PNW softwoods SE hardwoods SE softwoods	2005, 2010, updated 2013
Wood residue production	CORRIM data for residue production as a coproduct from the lumber production: PNW softwood lumber SE hardwood lumber SE softwood lumber NE-NC hardwood lumber NE-NC softwood lumber	 2015 2015 2012 2008 2010
Hydraulic fluid, Lubricants, motor oil, thermal fluid	USLCI data for "Gasoline, at refinery/l/US" without combustion emissions.	2008
Propane	USLCI data for "Liquefied petroleum gas, combusted in industrial boiler/US". Combustion emission removed if mill reported emissions	2008
Gasoline	USLCI data for "Gasoline, combusted in equipment/US". Combustion emission removed if mill reported emissions	2008
Diesel	USLCI data for "Diesel, combusted in industrial equipment/US." Combustion emission removed if mill reported emissions	2008
Natural gas	USLCI data for "Natural gas, processed, at plant/US." Combustion emission removed if mill reported emissions	2008
Slack Wax	CORRIM data for Slack wax obtained from the USLCI	2011
Potassium sulphate	Ecoinvent data, modified for US fuels and electricity	2003
Phenol formaldehyde resin	CORRIM data for production	2010
Plastic strapping/wrapping material	USLCI data for "Low density polyethylene resin, at plant/RNA"	2008
Metal strapping	USLCI data for "Hot rolled sheet, steel, at plant/RNA"	2008

4.2 Data Quality Requirements

This study collected data from representative hardboard manufacturers in North America that use average technology for their regions. The raw wood material to produce hardboard comes from a variety of co-products produced in product manufacturing facilities mills in Canada and the PNW, SE, and NE-NC regions of the United States in the form of green chips and green sawdust. The wood residue is comprised of many softwood species (Table 11)

Table 11 Possible species used in hardboard manufacturing, North America

Common Name	Latin Name
Douglas-fir	*Pseudotsuga menziesii*
red pine	*Pinus resinosa*
jack pine	*P. banksiana*
Virginia pine	*P. virginiana*
eastern white pine	*P. strobus*
loblolly pine	*P. taeda* L
quaking aspen	*Populus tremuloides*
basswood	*Tilia americana*
silver maple	*Acer saccharinum*
red maple	*A. rubrum*
sugar maple	*A. saccharum*
paper birch	*Betula papyrifera*
yellow birch	*B. alleghaniensis*
northern red oak	*Quercus rubra*
white oak	*Q. alba*
post oak	*Q. stellata*
chestnut oak	*Q. prinus*
swamp chestnut oak	*Q. michauxii*
laurel oak	*Q. laurifolia*
southern red oak	*Q. falcata*
southern live oak	*Q. virginiana*
black oak	*Q. velutina*
scarlet oak	*Q. coccinea*
blackjack oak	*Q. marilandica*
pin oak	*Q. palustris*
water oak	*Q. nigra*
willow oak	*Q. phellos*
yellow poplar	*Liriodendron tulipfera*
American gum	*Liquidamber styraciflua*

For the year 2012 when the study was initiated, seven hardboard facilities operated in North America. These seven facilities produced 2.20 billion ft^2 (205 million m^2) at 0.125-in (3.2-mm) basis equaling 22.9 million ft^3 (650 thousand m^3) of hardboard. Board production is measured on a thousand ft^2 (92.9 m^2) at 3.2-mm basis. The panels are typically produced in 0.125 up to 0.75 in (3.2–19.5 mm) thicknesses and in widths of 4.0 feet (1.22 m) and lengths of 8.0 (2.44 m) For

this study of hardboard production mills responding to surveys produced 792,865 m^3 in 2012, representing 42 percent of total production in North American. There were no operating hardboard plants in Mexico at the time of data collection.

4.3 Assumptions and Limitations

- All flow analyses of wood and bark in the process were determined on an oven-dry weight basis with a weighted average green specific gravity of 0.55.
- Wood dust collected from various hardboard processes including sanding is collected by bag houses and used as wood fuel.
- Roundwood delivered to the hardboard facilities was considered as fiber and the electricity required breaking down the material could not be separated out at the hardboard plant production. Therefore, the electricity used for grinding the roundwood into chips was accounted for under "hardboard production."

5 Life-cycle inventory analysis

5.1 Data Collection and calculation methods

Primary data for the LCI were collected through surveys in accordance with CORRIM and ISO 14040 standards. The study relied almost exclusively on production and emissions data provided by hardboard producers in North America, with some secondary data on electrical grid inputs and forest resource activities from the US LCI database (Goemans 2010; NREL 2012). The survey data represent hardboard production in terms of input materials, electricity, and fuel use, and emissions for the 2012 production year. The four production facilities surveyed were selected to be representative of North American production practices.

Questionnaires were used to survey the hardboard dry- and wet-process operations to collect primary data on hardboard manufacturing (Appendix B). The primary data obtained from the surveys were weight-averaged using the formula shown below (Milota 2004).

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

Where $\bar{P}_{weighted}$ is the weighted average of the values is reported by 'n' mills, P_i is the 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. Because the surveyed mill data varied between facilities, a statistical analysis was conducted. In the present study, the weighted coefficient of variation was calculated (NIST ITL 1996). The weighted coefficient of variation is the weighted standard deviation divided by the weighted mean:

$$sd = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}}$$

$$sd_w = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x}_w)^2}{\frac{(N'-1)\sum_{i=1}^{N} w_i}{N'}}}$$

Where w_i is the weight of the ith observation, 'N' is the number of non-zero weights, and $\bar{x}_w$ is the weighted mean of the observations.

Missing data are defined as data not reported in surveys by the hardboard facilities. Whenever missing data occurred for survey items, they were checked with plant personnel to determine whether it was an unknown value or zero. Missing data were carefully noted so they were not averaged as zeros. Any outliers were resolved by contacting mill personnel.

5.2 Calculation Rules

Hardboard is most commonly reported in a thousand square foot (MSF) 0.125-inch basis, which is equivalent to 0.295 m^3. The survey results were converted to a unit production basis of 1 m^3 (3.2-mm basis) and a weighted average of input data was calculated based on production. This approach resulted in a hardboard complex that represents a composite of the North American mills surveyed, but may not represent any mill in particular. The US LCI database was used to assess off-site impacts associated with the materials and energy used. SimaPro, version 8+ (Pré Consultants 2016) was used as the accounting program to track all of the materials.

The feedstock mass between input and output material flows in the production of hardboard were found to be within 1.7% (Table 12). The final product hardboard has an average oven-dry density of 768 kg/m^3 representing 94.8 percent wood fiber and 5.2 percent resin system. Table 11shows feedstock used in the production of the hardboard. Green pulp chips have the highest feedstock input at 624 OD kg per cubic meter of hardboard with roundwood at second with 168 OD kg. PF resin at 1.7 percent of total incoming raw material has the highest resin system portion at 15.3 OD kg/m^3 with paraffin wax contributing 13.6 OD kg. All of the co-products generated during hardboard production are used internally either as wood fuel or re-pulped. Most of the co-products came from the wood dust collection systems either as bag house or sander dust.

Table 12 Mass balance of hardboard manufacturing per m^3, North America (unallocated).

	Inputs		
	Oven dry mass (kg)	**Mass (%)**	**CoV (%)**
Feedstocks			
Roundwood	168	18.9	120
Chips, green	624	70.1	86.7
Sawdust, green	51	5.8	-
TOTAL FEEDSTOCK	843	94.8	13.8
Resin system			
Phenol-formaldehyde resin	15.3	1.7	45.9
Paraffin/wax emulsion	13.6	1.5	81.3
Zinc borate	6.9	0.8	-
Alum	5.1	0.6	76.4
Compregnite	4.2	0.5	-
Release agent	0.5	0.1	-
Slack wax	0.3	0.0	-
Linseed oil	0.1	0.0	-
TOTAL RESIN SYSTEM	46	5.2	15.9
TOTAL INPUT	**889**	**100**	**13.1**
	Outputs		
	Oven dry mass (kg)	**Mass (%)**	**CoV (%)**
Products			
Hardboard	768	86.3	12.0
Co-products			
Bag house dust, wood fuel	46.7	5.3	171
Culled boards, wood fuel	33.8	3.8	-
Sander dust, wood fuel	18.7	2.1	116
Dry sawdust, wood fuel	5.9	0.7	143
Bag house dust, re-pulped	1.4	0.2	-
Other, not specified	15	1.7	-
TOTAL CO-PRODUCTS	121	13.7	84.2
TOTAL OUTPUT	**889**	**100**	**15.3**

[a] Weighted coefficient of variation.

5.3 Allocation rules

If one or more co-products are generated during the production process, it is necessary to allocate the inputs and outputs using a standardized approach. The LCA on hardboard follows the allocation rules in the PCR (FPInnovations 2015) which states that when the total revenues between the main product and co-products is more than 10 percent, allocation shall be based on the revenue [economic] allocation. The 10 percent rule is applied based on a per unit basis, in this case per m^3 of hardboard. To ensure comparability with previous CORRIM wood product LCAs (http://www.corrim.org/pubs/reports.asp), this report also presents results based on mass allocation. Mass allocation results can be found in the subsequent sections of this report, while economic allocation results are located in Appendix A- Section 13 of this report.

5.4 Gate-to-gate LCI of hardboard manufacturing system

Table 13 summarizes the gate-to-gate flows of material and energy crossing the system boundary of hardboard. Under materials, wood feedstocks include wood material arriving at the production facilities either in roundwood form or already either fully or partially processed into wood residues. Roundwood in log form (168 OD kg) makes up 18.9 percent of the total hardboard feedstock on average for North America. Hardboard electricity consumed onsite is 654 kWh/m^3 (unallocated). On-site water usage for ground water and cooling water was 10,033 L/m^3, allocated. By far, cooling water was the highest representing 97 percent of the water consumed. Water recycling onsite was 69 percent leaving a net water consumption at 3,110 L/m^3, allocated.

Hardboard production air emission data were collected from surveyed mill data and augmented by secondary resources (USEPA 2002; Santos et al. 2007). The main emission sources outside of boilers are digesters/refiners, mat formers, hot presses, dryers, tempering ovens, humidification kilns, and sanding/finishing operations. Baghouses are the primary collectors of particulate matter with all four surveyed mills using emission control devices (ECD). To reduce VOC emissions from dryers and refiners, mills reported the use of regenerative thermal oxidizer (RTO), wet scrubbers, or biofiltration systems. RTO are designed to destroy VOCs and other emissions including PM and soot (USEPA 2003a). Bio-filtration systems, similar to a wet scrubber, also capture nitrous oxides, carbon monoxide, and other organic compounds such as formaldehyde (USEPA 2002).

If not reported in surveys, air emissions were derived from emission data categorized by the U.S. Environmental Protection Agency (USEPA 2002; USEPA 2003a; USEPA 2003b; USEPA 2003c; USEPA 2003d; DEQ 2006a; 2006b; Santos et al. 2007).

Table 13 Unit process inputs/outputs to produce 1 m^3 of hardboard, North American average, unallocated

Products	Value	Unit/m^3	Allocation (%)
Hardboard/Engineered wood siding and trim	1.0	m^3	86.3
Bag house dust, wood fuel	46.7	kg	5.2
Culled boards, wood fuel	33.8	kg	3.8
Sander dust, wood fuel	18.7	kg	2.1
Dry sawdust, wood fuel	5.9	kg	0.7
Bag house dust, re-pulped	1.4	kg	0.2
Other, not specified	15.0	kg	1.7
Resources	**Value**	**Unit/m3**	
Water, well, in ground	303	L	
Water, cooling, surface	11,323	L	
Materials/fuels	**Value**	**Unit/m3**	
Wood feedstock, average North America, oven-dried	844	kg	
Phenol-formaldehyde (PF) resin	15.3	kg	
Paraffin Emulsion (Wax)	13.6	kg	
Zinc Borate	6.92	kg	
Alum	5.09	kg	
Compregnite	4.18	kg	
Release agent	0.456	kg	
Slack Wax	0.306	kg	
Linseed oil	0.086	kg	
Electricity, at Grid	654	kWh	
Diesel, combusted in industrial equipment	3.56	L	
Gasoline, combusted in equipment	0.15	L	
LPG, combusted in industrial equipment	7.96	L	
Natural gas, combusted in industrial boiler	7.90	m^3	
Wood fuel, combusted in boiler, self-generated	318	kg	
Wood fuel, combusted in boiler, purchased	290	kg	
Residual fuel oil, combusted in industrial boiler	12	L	
Transport, combination truck, diesel power, purchased wood fuel	3.2	tkm	
Transport, combination truck, diesel power, wood feedstock	56.6	tkm	
Transport, combination truck, diesel powered, PF resin	5.76	tkm	
Transport, combination truck, diesel powered, paraffin wax	8.05	tkm	
Transport, combination truck, diesel powered, zinc borate	0.75	tkm	
Transport, combination truck, diesel powered, alum	1.20	tkm	
Transport, combination truck, diesel powered, Compregnite	0.45	tkm	
Transport, combination truck, diesel powered, release agent	0.05	tkm	
Transport, combination truck, diesel powered, slack wax	0.02	tkm	
Transport, combination truck, diesel powered, landfill waste	2.13	tkm	
Transport, combination truck, diesel powered, linseed oil	0.00	tkm	
Hydraulic fluid	0.38	kg	
Greases	0.04	kg	
Motor oil	0.02	kg	
Potable water	10.3	L	
Paint	8.99	L	
Ink	0.006	kg	
Wrapping material - Packaging	0.494	kg	
Strap Protectors - Packaging	1.42	kg	
Strapping - Packaging	0.330	kg	

Runners - Packaging	6.97	kg	
Emissions to air	**Value**	**Unit/m3**	**Comments**
Acetaldehyde	5.30E-02	kg	Primary
Acetone	1.74E-02	kg	
Acrolein	2.30E-02	kg	Primary
Alpha-pinene	8.08E-06	kg	
Benzene	3.57E-05	kg	Primary
Beta-pinene	1.31E-05	kg	
Carbon monoxide	2.06E-01	kg	
Chloroethane (Ethane, chloro-)	1.81E-05	kg	
Chloromethane (Methane, monochloro-,R-40)	1.71E-04	kg	
Cresols	7.71E-04	kg	
Cumene	0.00E+00	kg	
Ethylbenzene (Benzene, ethyl)	4.57E-05	kg	
Formaldehyde	6.93E-02	kg	Primary
Formic acid	7.85E-02	kg	Primary
Hexaldehyde (hexanal)	1.69E-02	kg	
Lead	0.00E+00	kg	
Limonene	7.24E-04	kg	
Mercury	0.00E+00	kg	
Methanol	3.08E-01	kg	Primary
Methyl ethyl ketone	3.41E-03	kg	
Methyl isobutyl ketone	7.85E-03	kg	
Nitroux oxide	4.00E-03	kg	
NMVOC, unspecified origin[b]	0.00E+00	kg	
PM2.5	0.00E+00	kg	
PM10	8.91E-02	kg	
Particulates, > 2.5 um, and < 10um	8.91E-02	kg	
Particulates, unspecified	1.47E-01	kg	
Phenol	9.42E-02	kg	Primary
Propionaldehyde (propanal)	1.79E-01	kg	Primary
Styrene	0.00E+00	kg	
Sulfur dioxide	3.07E-01	kg	Primary
Toluene	1.85E-03	kg	
Total hydrocarbons	1.99E+00	kg	
VOC, volatile organic compounds	1.40E+00	kg	Primary
Xylenes	7.66E-05	kg	
Emissions to water	**Value**	**Unit/m3**	
BOD5, Biological Oxygen Demand	2.0	kg	Primary
COD, Chemical Oxygen Demand	7.7	kg	Primary
Suspended solids, unspecified	3.8	kg	Primary
Waste to treatment	**Value**	**Unit/m3**	
Waste to inert landfill	42.6	kg	Primary
Waste to recycling	26.5	kg	Primary

[a] Non-methane volatile organic compound

5.5 Cradle-to-gate LCI results

Cradle-to-gate life-cycle inventory results for hardboard are presented by three life stages, 1) forestry operations, 2) wood residue production, and 3) hardboard production (Tables 14-18). The majority of the raw material energy consumption occurs during hardboard production, followed by the production of the wood residue with only a very small portion arising from forestry operations. By mass, wood fuel is the dominant fuel used (72% or 765 kg/m^3) and is consumed entirely during hardboard production as no drying of feedstock during wood residue production was performed before arriving at the hardboard plants. Wood fuel was burned onsite to generate onsite thermal energy and off-site at a sawmill facility to produce wooden runners for the final product. Coal at 173 kg/m^3 was used primarily to generate electricity and represents 16 percent of the raw fuel consumed.

Table 14 Raw material energy consumption per 1 m^3 of hardboard, North American average (mass allocation)

			Forest Operations	Residue production	Hardboard production	Total	
Coal, in ground		kg	0.34	8.07	165	173	16%
Gas, natural, in ground		kg	0.20	0.73	40	41	4%
Oil, crude, in ground		kg	5.17	3.30	77	86	8%
Uranium oxide, in ore		kg	0.00	0.00	0.01	0.01	0%
Wood fuel		kg	0.00	1.66	763	765	72%
Total			5.71	13.76	1,046	1,065	100%
			1%	1%	98%	100%	

Table 15 shows the cumulative energy consumption for the cradle-to-gate production of hardboard. Hardboard production consumed the most primary energy at 29,020 MJ/m^3 (97%). Most of the primary energy was derived from wood fuel at 16,781 MJ/m^3 and fossil fuels 10,724 MJ/m^3 with cumulative energy consumption for all three life-cycle stages at 29,834 MJ/m^3.

Table 15 Cumulative energy consumption per 1 m3 of cradle-to-gate hardboard, North American average (mass allocation).

	Forest Operations	Residue production	Hardboard production	Total
	MJ/m^3			
Non-renewable fossil	255	426	10,043	10,724
Non-renewable nuclear	3	85	2,057	2,145
Renewable (solar, wind, hydroelectric, and geothermal)	0	9	176	185
Renewable, biomass	0	36	16,744	16,781
Total	258	556	29,020	29,834

Hardboard manufacturers reported onsite air emissions (Table 16) including particulate and particulate PM_{10} (less than 10 µm in size) that are emitted during refining, drying, and trimming. Other air emissions include VOCs from drying and pressing. Fossil and biogenic CO_2 released in the production of 1 m^3 of hardboard were 617 and 925 kg, respectively. A complete list of all air

emissions for the cradle-to-gate production of hardboard can be found in Appendix B. Boiler emissions are tracked separately and are not included in Table 16.

Table 16 Air emissions released per 1 m^3 of hardboard, North American average (mass allocation)

Substance[a]	Forest operations	Wood residue production	Hardboard production	Total
Acetaldehyde	6.99E-05	1.40E-04	4.64E-02	4.66E-02
Acetone	0.00E+00	0.00E+00	1.50E-02	1.50E-02
Acrolein	8.47E-06	6.24E-05	2.03E-02	2.04E-02
Aldehydes, unspecified	2.10E-04	1.37E-04	2.72E-03	3.07E-03
alpha-Pinene	0.00E+00	0.00E+00	6.97E-06	6.97E-06
Ammonia	1.06E-04	1.03E-04	9.47E-03	9.68E-03
Ammonium chloride	3.48E-07	1.19E-05	2.86E-04	2.98E-04
Benzene	8.52E-05	7.34E-05	2.91E-04	4.49E-04
Benzene, ethyl-	6.62E-12	7.31E-09	3.95E-05	3.95E-05
Beta-Pinene	0.00E+00	0.00E+00	1.13E-05	1.13E-05
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	7.05E-05	2.56E-04	1.39E-02	1.43E-02
Carbon dioxide	0.00E+00	2.08E-03	1.95E-01	1.97E-01
Carbon dioxide, biogenic	1.57E-02	4.86E+00	9.20E+02	9.25E+02
Carbon dioxide, fossil	1.68E+01	2.81E+01	5.72E+02	6.17E+02
Carbon monoxide	3.44E-06	8.29E-03	8.35E-01	8.44E-01
Carbon monoxide, biogenic	0.00E+00	3.36E-03	1.67E+00	1.67E+00
Carbon monoxide, fossil	1.45E-01	7.49E-02	1.05E+00	1.27E+00
Cresol	0.00E+00	0.00E+00	6.65E-04	6.65E-04
Dinitrogen monoxide	1.33E-05	2.40E-04	1.03E-02	1.06E-02
Ethane, chloro-	2.96E-12	7.79E-11	1.56E-05	1.56E-05
Formaldehyde	1.08E-04	9.37E-05	8.89E-02	8.91E-02
Formic acid	0.00E+00	0.00E+00	6.77E-02	6.77E-02
HAPs	0.00E+00	6.52E-06	3.24E-03	3.25E-03
Heat, waste	0.00E+00	4.18E-03	3.80E+00	3.81E+00
Hexanal	0.00E+00	0.00E+00	1.37E-02	1.37E-02
Hydrocarbons, unspecified	2.01E-06	6.85E-05	1.72E+00	1.72E+00
Hydrogen chloride	1.90E-04	4.46E-03	8.93E-02	9.40E-02
Hydrogen fluoride	2.24E-05	5.22E-04	1.07E-02	1.12E-02
Isoprene	3.95E-04	9.51E-03	2.55E-01	2.65E-01
Kerosene	1.67E-07	5.68E-06	1.37E-04	1.43E-04
Lead	8.99E-08	2.36E-06	1.29E-04	1.31E-04
Limonene	0.00E+00	0.00E+00	6.25E-04	6.25E-04
Magnesium	1.64E-06	3.83E-05	7.82E-04	8.22E-04
Metals, unspecified	4.47E-14	5.79E-04	1.77E-08	5.79E-04
Methane	2.19E-02	4.87E-02	1.34E+00	1.41E+00
Methane, biogenic	0.00E+00	2.32E-05	1.15E-02	1.15E-02
Methane, fossil	1.55E-03	2.12E-03	9.67E-02	1.00E-01
Methane, monochloro-, R-40	3.74E-11	9.83E-10	1.48E-04	1.48E-04
Methanol	0.00E+00	1.11E-04	2.70E-01	2.71E-01
Methyl ethyl ketone	2.75E-11	7.23E-10	2.94E-03	2.94E-03
Nickel	1.33E-06	2.84E-06	4.20E-04	4.25E-04
Nitrogen oxides	3.05E-01	1.48E-01	2.72E+00	3.18E+00
NMVOC, non-methane volatile organic compounds, unspecified origin	1.02E-02	7.25E-03	1.39E-01	1.56E-01
Organic substances, unspecified	9.27E-07	2.57E-05	2.45E-03	2.47E-03
Other Organic	0.00E+00	2.20E-07	1.09E-04	1.09E-04
Particulates, < 10 um	0.00E+00	4.99E-04	3.20E-01	3.21E-01
Particulates, < 2.5 um	0.00E+00	8.10E-04	7.36E-02	7.44E-02
Particulates, > 10 um	0.00E+00	1.80E-03	2.34E-03	4.15E-03
Particulates, > 2.5 um, and < 10um	9.39E-03	9.83E-03	4.22E-02	6.14E-02

Substance[a]	Forest operations	Wood residue production	Hardboard production	Total
Particulates, unspecified	1.69E-03	3.16E-01	2.18E+00	2.50E+00
Phenol	1.13E-12	8.06E-07	1.04E-01	1.04E-01
Propanal	2.68E-11	9.75E-07	4.58E-02	4.58E-02
Propene	2.35E-04	3.16E-05	1.64E-04	4.31E-04
Radionuclides (Including Radon)	9.33E-06	3.18E-04	7.66E-03	7.98E-03
Selenium	2.07E-07	4.62E-06	9.64E-05	1.01E-04
Sulfur dioxide	9.42E-03	1.26E-01	3.49E+00	3.62E+00
Sulfur monoxide	1.69E-02	1.12E-02	3.72E-01	4.00E-01
Sulfur oxides	0.00E+00	4.36E-04	3.17E-02	3.22E-02
TOC, Total Organic Carbon	0.00E+00	5.54E-05	1.59E-09	5.54E-05
Toluene	3.73E-05	5.02E-06	1.62E-03	1.66E-03
VOC, volatile organic compounds	7.99E-03	7.54E-03	1.72E+00	1.74E+00
Wood (dust)	0.00E+00	1.43E-03	2.91E-01	2.92E-01
Xylene	2.60E-05	3.49E-06	8.43E-05	1.14E-04

[a] Due to large amount of water emissions, emissions greater than of 10-4 and HAPs generated from hardboard production are shown. A complete list of all air emissions can be found in APPENDIX B.

Waterborne emissions produced are shown in Table 17. Suspended solids, with a value of 25.5 kg/m^3 and chloride at 17.2 kg/m^3 were two largest water borne emissions. For suspended solids, most of this was a result of crude oil production and natural gas extraction followed by onsite hardboard production itself. Most of chloride emission was from producing PF resin and alum used to form the panels and thus did not occur at the hardboard production facilities.

Table 17 Emissions to water released per 1 m^3 of hardboard, North American average (mass allocation)

Substance	Forest operations	Wood residue production	Hardboard production	Total
Acidity, unspecified	0.00E+00	7.69E-14	1.49E-03	1.49E-03
Acids, unspecified	2.53E-10	1.74E-08	3.17E-04	3.17E-04
Aluminium	1.67E-03	1.20E-03	2.93E-02	3.21E-02
Ammonia	3.61E-04	2.69E-04	7.33E-03	7.96E-03
Arsenic	5.28E-06	4.06E-06	1.14E-04	1.24E-04
Barium	2.28E-02	1.53E-02	3.74E-01	4.12E-01
Benzene	3.23E-05	2.57E-05	7.41E-04	7.99E-04
Benzoic acid	1.95E-05	1.52E-05	4.49E-04	4.83E-04
BOD5, Biological Oxygen Demand	3.52E-03	2.91E-02	1.81E+00	1.84E+00
Boron	6.05E-05	4.70E-05	1.39E-03	1.50E-03
Bromide	4.13E-03	3.21E-03	9.47E-02	1.02E-01
Calcium	6.19E-02	4.81E-02	1.42E+00	1.53E+00
Chloride	6.96E-01	5.41E-01	1.60E+01	1.72E+01
Chromium	4.39E-05	2.81E-05	6.29E-04	7.01E-04
Chromium III	3.31E-06	3.40E-06	1.25E-04	1.31E-04
COD, Chemical Oxygen Demand	6.69E-03	5.08E-03	6.77E+00	6.78E+00
Copper	5.49E-06	6.19E-06	1.59E-04	1.71E-04
Detergent, oil	1.62E-05	1.30E-05	3.97E-04	4.26E-04
Fluoride	1.21E-06	8.98E-05	1.01E-03	1.10E-03
Iron	3.32E-03	2.48E-03	6.21E-02	6.79E-02
Lead	1.11E-05	8.40E-06	2.22E-04	2.41E-04
Lithium	9.93E-04	3.55E-03	1.93E-01	1.97E-01
Magnesium	1.21E-02	9.41E-03	2.78E-01	2.99E-01
Manganese	2.17E-05	8.35E-05	1.95E-03	2.05E-03
Nickel	5.21E-06	3.80E-06	1.04E-04	1.13E-04
Nitrogen, total	1.85E-07	7.07E-06	2.20E-04	2.27E-04
Oils, unspecified	4.45E-04	3.69E-04	1.03E-02	1.11E-02
Organic compounds (dissolved)	0.00E+00	0.00E+00	1.92E-04	1.92E-04
Phenol	8.18E-06	5.21E-06	1.19E-04	1.32E-04
Phosphate	0.00E+00	3.65E-05	1.15E-04	1.51E-04
Silver	4.05E-05	3.15E-05	9.28E-04	1.00E-03
Sodium	1.96E-01	1.53E-01	4.50E+00	4.85E+00
Solved substances, inorganic	0.00E+00	0.00E+00	2.55E-04	2.55E-04
Strontium	1.05E-03	8.17E-04	2.41E-02	2.60E-02
Sulfate	1.55E-03	6.23E-03	1.56E-01	1.64E-01
Sulfide	9.49E-07	2.68E-06	1.80E-04	1.84E-04
Sulfur	5.10E-05	3.97E-05	1.17E-03	1.26E-03
Suspended solids, unspecified	9.09E-01	7.03E-01	2.38E+01	2.55E+01
Titanium	1.60E-05	1.06E-05	2.57E-04	2.84E-04
Toluene	3.05E-05	2.38E-05	7.01E-04	7.55E-04
Waste water/m3	0.00E+00	1.29E-02	2.49E-03	1.54E-02
Water	0.00E+00	5.81E+00	0.00E+00	5.81E+00
Xylene	1.64E-05	1.27E-05	3.71E-04	4.00E-04
Zinc	3.85E-05	2.97E-05	7.28E-04	7.96E-04

Solid emissions include ash generated onsite at the boiler and in the upstream processes, primarily fuels and resins, used in hardboard production (Table 18). A total of 126.17 kg/m^3 solid waste was generated with 14 percent generated onsite, 18 percent recycled, and 68 percent going to the landfill.

Table 18. Waste to treatment per 1 m^3 of hardboard, North American average (mass allocation)

Waste to treatment	Forest operations	Wood residue production	Hardboard production	Total
	kg/m3			
Waste generated on site	0.04	0.72	17.01	17.77
Waste to recycling	0	0.11	22.87	22.98
Waste disposal	0.27	4.22	80.96	85.42
Total	0.31	5.05	120.84	126.17

6 Life-cycle impact assessment results

The life cycle impact assessment (LCIA) phase establishes links between the life cycle inventory results and potential environmental impacts. The LCIA calculates impact indicators, such as global warming potential and smog. These impact indicators provide general, but quantifiable, indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 16. Environmental impacts are determined using the TRACI method (Bare et al. 2011). These five impact categories are reported consistent with the requirement of the PCR (FPInnovations 2015).

Table 19 Selected impact indicators, characterization models, and impact categories.

Impact Indicator	Characterization Model	Impact Category
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of ozone layer	Calculate the total ozone forming chemicals in the stratosphere including CFC's HCFC's, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion (SO_2) equivalent for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. Acidification value of SO_2 mole-eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate total substances that can be photo-chemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication

Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning that no single indicator is given more or less value than any of the others. All are presented as equals. Additionally, each impact indicator value is stated in units that are not comparable to others. For the same reasons, indicators should not be combined or added. Table 20 provides the environmental impact by category for hardboard. In addition, energy and material resource consumption values and the waste generated are also provided.

Environmental performance results for global warming potential (GWP), acidification, eutrophication, ozone depletion and smog, energy consumption from non-renewables, renewables, wind, hydro, solar, and nuclear fuels, renewable and nonrenewable resources, and solid waste are shown in Table 20. For GWP, 98.5 percent of the CO_2 eq. emissions come from producing hardboard. Similar results are presented for acidification, eutrophication, and smog, representing 93, 87, and 96 percent contributed from hardboard production, respectively.

Renewable-biomass fuel represented the greatest proportion of energy consumed (56%) for total cradle to gate primary energy use. Non-renewable fossil fuels and non-renewable nuclear represented 36 and 7 percent of the total primary energy, respectively. Of the three life cycle stages considered in this study, hardboard production consumes 97 percent of the total primary energy consumption. Overall, the manufacture of hardboard in North America is over 56 percent energy self-sufficient with its use of renewable biomass. Water intake is high for the cradle-to-gate production of hardboard at over 10,000 L/m^3. While this number is high, 69 percent of this usage is recycled, resulting in a net water consumption of 3,110 L/m^3. It is clear that water conservation measures currently in place in North American hardboard facilities have made a dramatic impact in the reduction of water consumption.

Table 20 Environmental performance of 1 m^3 hardboard, North American average (mass allocation).

Impact category	Unit	Total	Forestry operations	Wood residue production	Hardboard production
Global warming potential (GWP)	kg CO_2 eq	658.48	17.43	29.43	611.62
Acidification Potential	kg SO_2 eq	6.39	0.24	0.25	5.91
Eutrophication Potential	kg N eq	0.58	0.01	0.01	0.56
Ozone depletion Potential	kg CFC-11 eq	0.000	0.0000	0.0000	0.0000
Smog Potential	kg O_3 eq	90.02	7.60	3.81	78.61
Total Primary Energy	MJ	29,834	258	556	29,020
Non-renewable fossil	*MJ*	*10,724*	*255*	*426*	*10,043*
Non-renewable nuclear	*MJ*	*2,145*	*3*	*85*	*2,057*
Renewable (solar, wind, hydroelectric, and geothermal)	*MJ*	*185*	*0*	*9*	*176*
Renewable, biomass	*MJ*	*16,780*	*0*	*36*	*16,744*
Material resources (non fuel)	**Unit**	**Total**	**Forestry operations**	**Wood residue production**	**Hardboard production**
Non-renewable materials	kg	5.04	0	0.07	4.97
Renewable materials	kg	609.68	0	29.88	579.80
Fresh water	L	10,054	0.00	15	10,039
Waste generated	**Unit**	**Total**	**Forestry operations**	**Wood residue production**	**Hardboard production**
Solid waste	kg	126.17	0.31	5.05	120.84

7 Carbon

Treatment of biogenic carbon is consistent with the Intergovernmental Panel for Climate Change (IPCC 2006) inventory reporting framework. There is no assumption that biomass combustion is carbon neutral, but that net carbon emissions from biomass combustion are accounted for under the Land-Use Change and Forestry (LUCF) Sector and are therefore ignored in energy emissions reporting for the product LCA to prevent double counting. Standards such as ASTM D7612, which are used in North America to define legal, responsible and/or certified sources of wood materials, are in place to provide assurances regarding forest regeneration and sustainable harvest rates that serve as proxies to ensure stable carbon balances in the forest sector. They are outside the accounting framework for this LCA.

This approach to the treatment of biogenic carbon was taken for the Norwegian Solid Wood Product PCR (Aasestad 2008), and the North American PCR has adopted an identical approach to ensure comparability and consistency. The North American PCR approach is followed here for GWP reporting therefore the default TRACI impact assessment method was used. This default method does not count the CO_2 emissions released during the combustion of woody biomass during production. Other emissions associated from wood combustion, e.g., methane or nitrogen oxides, do contribute to and are included in the GWP impact category. For a complete list of emissions factors for the GWP method used, see Bare et al. (2011). Using this method, 658 kg CO_2e were released in the production of 1 m^3 of hardboard. That same 1 m^3 of hardboard stores 364 kg of carbon[4] or 1,335 kg CO_2 eq.[5], resulting in more carbon storage in the product then released during manufacturing (cradle to gate) (Table 21).

Table 21 Carbon per 1 m^3 hardboard, North American average (mass allocation).

	kg CO_2 equivalent
released forestry operations	17
released hardboard and residue manufacturing	641
CO_2 eq. stored in product	1,335

[4] Assuming a 50% carbon content

[5] 728 OD kg of wood in hardboard × (0.5 kg carbon/1.0 OD kg wood) × (44 kg CO_2/kmole/12 kg carbon/kmole) = 1335 kg CO_2 eq.

8 Life Cycle Interpretation

As defined by ISO (2006), life cycle interpretation is the phase of the LCA that the findings of either the LCI or the LCIA, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations. This phase in the LCA reports the significant issues based on the results of the presented in LCI and the LCIA of this report. Additional components report an evaluation that considers completeness, sensitivity and consistency checks of the LCI and LCIA results, conclusions, limitations, and recommendations.

8.1 Identification of the significant issues

The objective of this element is to structure the results from the LCI or the LCIA phases in order to help determine the significant issues found in the results as presented in previous sections of this report. A contribution analysis was applied for the interpretation phase of this LCA study. Contribution analyses examines the contribution of life cycles stages, unit process contributions in a multi-unit manufacturing process, or specific substances which contribute particular impact categories.

8.2 Life cycle phase contribution analysis

Three life cycle stages were used in the overall cradle-to-gate assessment of hardboard. Their contribution to impact categories varied depending on whether mass or economic allocation was applied. Table 22 shows the contribution difference to several impact measures for both mass and economic allocation. Economic allocation resulted in a slight increase in the hardboard life cycle stage due to all burdens shifted towards the production of hardboard and zero percent to all co-products. Production of the wood residues had the most significant influence on impact measures depending on the allocation methods applied. Applying an economic allocation resulted 1 percent to 62 percent decrease in all impact categories and energy consumption for residue production. The overall CtG production resulted in less than a 5 percent difference between economic and mass allocation methods for all impact measurements.

Table 22 Life cycle stages contribution analysis of 1 cubic meter (m^3) of hardboard (mass and economic allocation)

		Mass Allocation			Economic Allocation		
Impact category	**Unit**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Ozone depletion	kg CFC-11 eq	0.0%	1.5%	98.5%	0.0%	0.5%	99.5%
Global warming	kg CO2 eq	2.6%	4.5%	92.9%	2.3%	2.3%	95.4%
Smog	kg O3 eq	8.4%	4.2%	87.3%	7.5%	2.3%	90.1%
Acidification	kg SO2 eq	3.8%	3.8%	92.4%	3.3%	1.8%	94.8%
Eutrophication	kg N eq	2.5%	1.5%	96.1%	2.2%	0.8%	97.1%
Primary Energy	**Unit**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Total	MJ	0.9%	1.9%	97.3%	1.6%	1.8%	96.5%
Non-renewable fossil	*MJ*	2.4%	4.0%	93.7%	2.1%	2.0%	95.9%
Non-renewable nuclear	*MJ*	0.1%	4.0%	95.9%	0.1%	1.6%	98.3%
Renewable (solar, wind, hydroelectric, and geothermal)	*MJ*	0.2%	4.7%	95.1%	0.1%	1.6%	98.2%
Renewable, biomass	*MJ*	0.0%	0.2%	99.8%	0.0%	0.0%	100.0%
Material resources consumption (Non-fuel resources)	**Unit**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Non-renewable materials	kg	0.0%	1.5%	98.5%	0.0%	0.2%	99.8%
Renewable materials	kg	0.0%	4.9%	94.8%	0%	2%	83%
Fresh water	L	0.0%	0.1%	99.9%	0.0%	0.1%	99.9%
Waste generated	**Unit**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Solid waste	kg	0.2%	4.0%	95.8%	0.2%	1.4%	98.4%

8.3 Substance contribution analysis

The impact indicators presented in the LCIA results (Table 20) in this report do not show how each of the substance releases (Table 16) within each of the life cycle stages contributes to individual impact indicators. Highlighting particular substances can result in a more focused approach to making process improvements therefore saving time and money. Table 23 lists the level of contribution of the 3 main GHG emissions (fossil CO_2, CH_3, and N_2O) to global warming potential (GWP) of the three life cycle stages for hardboard manufacturing. Both mass and economic allocation results are presented.

Table 23 Substance contribution1/ analysis to Global Warming Potential (kg CO_2 eq.) by life cycle stage total percent basis and values are displayed per 1.0 m^3.

		Mass Allocation				Economic Allocation			
GWP substances	**Compartment type**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Total of all compartments		**100.00%**	17.43	29.43	611.62	**100.00%**	17.43	16.98	708.84
Carbon dioxide, fossil (CO_2)	Air	**93.75%**	16.84	28.09	572.43	**93.71%**	16.84	16.25	663.42
Methane (CH_4)	Air	**5.77%**	0.59	1.27	36.11	**5.80%**	0.59	0.68	41.85
Dinitrogen monoxide (N_2O)	Air	**0.48%**	0.00	0.07	3.08	**0.49%**	0.00	0.06	3.57
Remaining substances	Air	**0.00%**	0.00	0.00	0.00	**0.00%**	0.00	0.00	0.00

1/ additional substance contributions for other impact categories can be found in Appendix C of this report

8.4 Completeness, sensitivity and consistency checks

Evaluating the LCA's completeness, sensitivity, and consistency offers confidence in the reliability of the LCA results. The ***completeness check*** process verifies whether information from the life cycle phases of a LCA are sufficient for reaching the goals and scope and conclusions of the study and making sound interpretations of the results. Three life cycle stages (forestry operations, wood residue production, and hardboard production) were checked for data completeness including all input elements such as raw and ancillary materials input, energy input, transportation scenarios, water consumption, and outputs such as products and co-products, emissions to air, water, land, and final waste disposals. All input and output data were found to be complete and no data gaps were identified.

The ***Consistency check*** process verifies that the assumptions, methods and data are consistently applied throughout the study and are in accordance with the goal and scope of the LCA. A comprehensive review process was completed to this LCA to make certain consistency was applied to the assumptions made, methods used, models, data quality including data sources, and data accuracy, age, time-related coverage, technology, and geographical coverage.

Sensitivity analysis can be applied to the LCA to determine changes in results due to variations in assumptions, methods, and data. A sensitivity check was performed on this LCA contrasting the mass and economic allocation methods. This LCA used mass allocation method, similar to previous LCA's on wood products. To stay within conformance with the PCR (2015), an economic allocation was required on the data. Hardboard is primarily a single-output product (86.3% by mass) with approximately 1.7 percent coproduct leaving the system, and the remaining 12 percent re-entering the system as a fuel source or re-pulped wood. For the economic allocation methods, no allocation was applied to the hardboard product. Most of the wood residue inputs to hardboard production, however, are the co-products of hardwood and softwood lumber manufacturing. Lumber production results in multiple valuable products, such as green rough lumber, planed green and dry lumber and several variety of co-products (i.e. pulp

chips, sawdust, shavings). When either mass or economic allocation is applied, the total environmental burden is "shared" between the primary product (lumber) and the co-products (chips, etc.) based on total mass or total value (sales) respectively. In this LCA, wood residue values were based on prices published in Random Lengths (2012) for the year data were collected from hardboard manufacturers. Figures 7 and 8 graphically display the two allocation methods side by side across impact indicators for hardboard and wood residue production, respectively. This sensitivity analysis does show that the allocation method does have an influence on certain impact indicators and is highly dependent on the life cycle stage. When an economic allocation approach was applied all impact indicators resulted in an 11 to 16 percent increase over a mass allocation approach in the hardboard life cycle stage (Figure 7). On the other hand, when the allocation approach was applied to residue production every impact category was lowered over a mass allocation by 1 to 62 percent (Figure 8). Biomass energy showed only a 1% change between mass and economic approaches, while GWP, acidification, eutrophication, and smog resulted 58, 53, 51, and 62 percent decrease, respectively. Fossil and nuclear energy were also significantly lowered by 57 and 45 percent, respectively. This decrease in impact contribution from wood residue production occurred because when economic allocation was assigned to lumber production, far more of the environmental impacts were assigned to lumber than to the coproducts that are used in the production of hardboard.

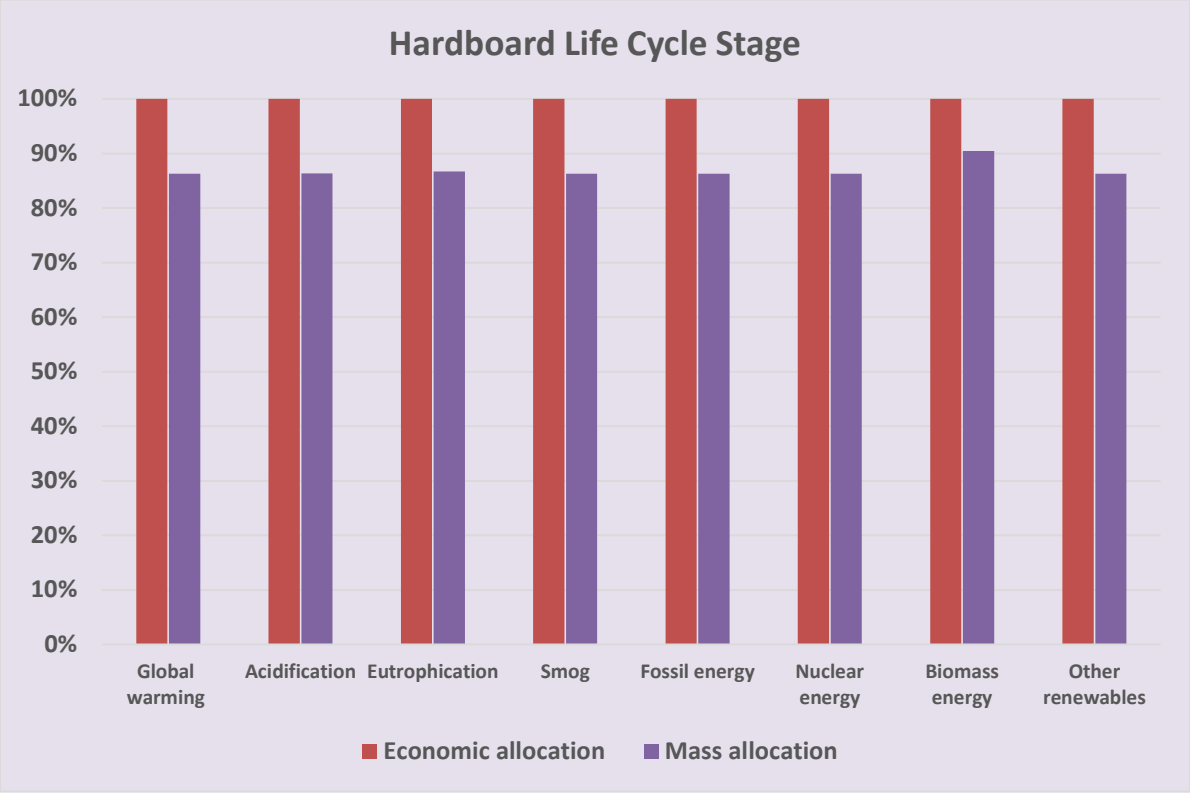

Figure 7 Sensitivity analysis for the gate-to-gate hardboard life cycle stage comparison between mass and economic allocation methods.

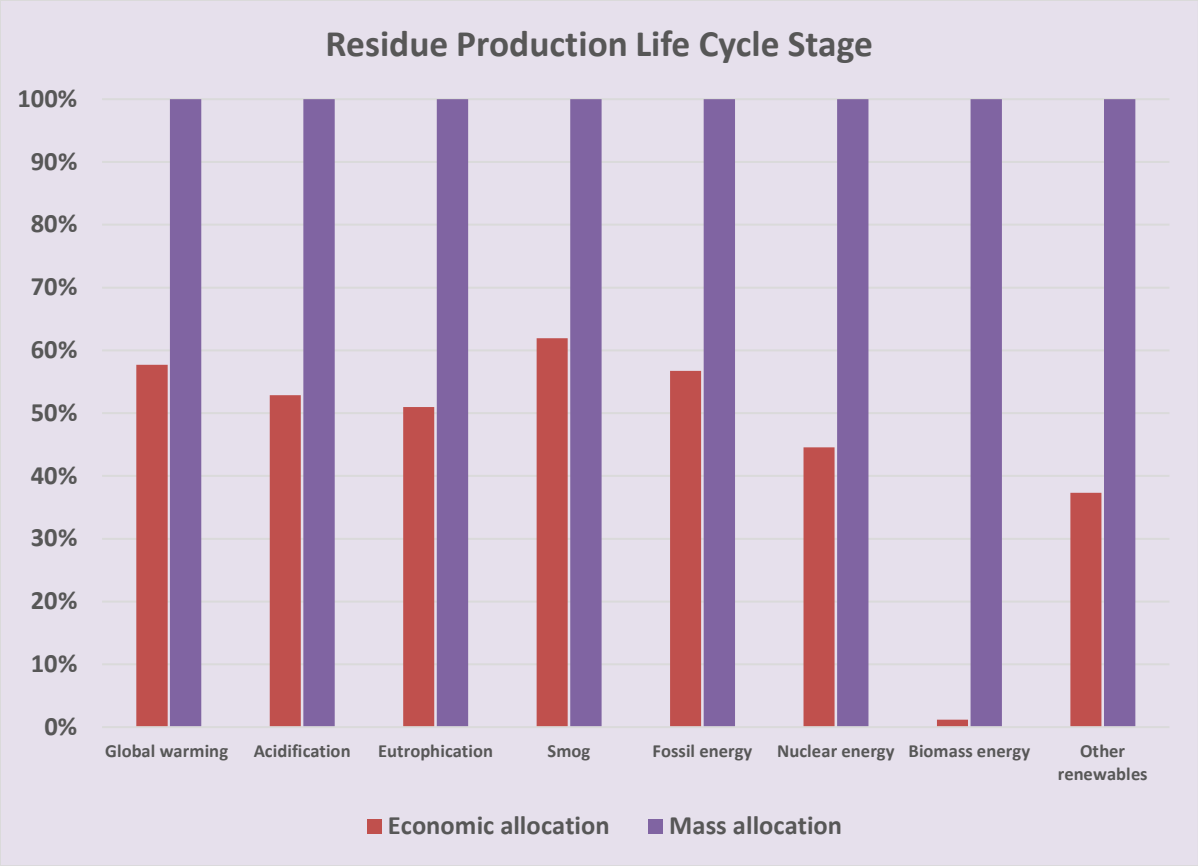

Figure 8 Sensitivity analysis for the gate-to-gate wood residue life cycle stage comparison between mass and economic allocation methods.

9 Conclusions, limitations, and recommendations

Emissions from the forest resources LCI are small relative to manufacturing emissions (wood residue and hardboard). At the hardboard production facility, emissions originate at the boiler, during drying, refining, forming, pressing, tempering, and humidifying. Boiler emissions released are a function of the fuel burned while other emissions are a function of the unit process and associated emission control devices.

Cradle-to-gate LCI results showed 659 kg CO_2e were released in the production of 1 m^3 of hardboard. However, hardboard stores carbon. Carbon content for wood products is assumed to be 50 percent by mass of OD wood. Excluding the resin system, the carbon stored in the wood portion of 1 m^3 (728 OD kg) of hardboard is equivalent to 1,335 kg CO_2 emissions.

Wood products typically consume more energy during the manufacturing stage than any other stage (Puettmann and Wilson 2005; Winistorfer et al. 2005; Puettmann et al. 2010). Primary energy is the energy embodied in the original resource such as crude oil and coal before any conversion processes. For reference, making medium-density fiberboard (MDF) in the United States, cumulative embodied energy in 1 m^3 of MDF is 19.7 GJ/m^3, with 41 percent from wood

fuel (Wilson 2010b; Puettmann et al 2013a). In oriented strandboard (OSB) production, the embodied energy is 11.0 GJ/m^3, for 1 m^3 of OSB is with 38% from wood fuel (Kline 2005). The values for MDF and OSB use mass allocation. In Europe, González-García and others (2009) did not report a cumulative embodied energy for conventional hardboard production but a later study (González-García et al. 2011) did report an embodied energy value of 6.23 GJ/m^3 based on lower-heating values (LLVs) for the energy consumed for a 'green' hardboard using a laccase-activated system.

Amount and type of energy has a substantial role during production of building materials. Total cumulative energy consumption for the cradle-to-gate production of hardboard was 29.8 GJ/m^3. Use of renewable energy in manufacturing hardboard was substantial. Renewable energy made up over 56% of the total cumulative energy consumption profile for hardboard production. Renewable biomass was by far the largest renewable energy source. It represents 56.2 percent of the total cumulative energy consumption for all stages of production and 57.7 percent within the hardboard life cycle state. When an economic allocation was performed, the contribution of renewable biomass was slightly lower for both the total (all stages) and hardboard production at 55.6 and 56.6 percent, respectively. The shift in energy distribution was in the residues. When a mass allocation was applied, renewable biomass contributed almost 7 percent in the residue production life cycle stage. On an economic basis, the contribution was less than a half percent (0.15%).

Forestry operations consumed relatively little energy overall (<1%, mass allocation) and were exclusively fossil fuels (99%). Wood residue production also consumed very energy compared to the total (<2%), and with the majority of the energy coming from non-renewable fossil fuel (77%). Energy consumed during PF resin production along with the additives was included in the fossil fuel use for hardboard as an upstream process.

In summary, when a mass allocation approach was used, 1 m^3 of hardboard from cradle-to-gate, 56 percent of the cumulative energy was from renewable biomass and 36 percent from non-renewable fossil fuels leaving a small portion of energy needs coming from nuclear (7%) and other renewable sources (hydro, wind, solar, and geothermal)(<1%). Total energy consumed on a mass basis is 29.8 GJ/m^3. When an economic allocation approach is applied, more burden is shifted toward hardboard production and the overall energy consumption is increased by 12 percent.

Cradle to gate carbon impacts for 1 m^3 hardboard production show 658 kg CO_2e were released. However carbon is retained within the hardboard for long term storage resulting in equivalent 1,335 kg CO_2. More carbon is stored than is released during hardboard production.

Three substantive issues are revealed from the cradle-to-gate LCI of hardboard. Of note is the significant amount of water used in the production process. However, it is noted that recycling efforts have substantially reduced overall water consumption. In addition, wood fuel consumption in hardboard production greatly lowers fossil carbon dioxide emissions which are the major contribution toward the global warming impact. Therefore, every effort to maintain or increase wood fuel consumption where practicable ought to be considered to help mitigate the global warming impact. Last, using green instead of dry wood residue lowers the energy

consumed in the preparation of feedstock in the hardboard production stage. Therefore, green wood residue should continue to be used as a feedstock over dry wood residues.

10 Critical review

10.1 Internal review

An internal review of the LCA product was provided by Dr. Richard Bergman and Dr. Elaine Oneil; both of which are knowledgeable and experienced LCA and wood products reviewers. The LCI report (Bergman 2015) also had undergone a peer-review process before publishing. The purpose of the LCA report internal review is to check for errors and conformance with the PCR prior to submittal for external review. The technical and editorial comments of the reviewers were carefully considered and in most instances incorporated into the final document.

10.2 External review

The external review process is intended to ensure consistency between the completed LCA and the principals and requirements of the International Standards on LCA (ISO 2006a) and the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (FPInnovations 2015). Following CORRIM's internal review, documents were submitted to UL Environment (ULE) for independent external review. The independent external review performed by ULE was conducted by:

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UL Environment
UL LLC
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Marietta, GA 30067 USA
Mobile: 678.469.3598; Office: 678.444.4046

The external review process is intended to ensure consistency between the completed LCA and the principals and requirements of the International Standards on LCA (ISO 2006a) and the Product Category Rules (PCR) for North American Structural and Architectural Wood Products (FPInnovations 2015).

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12 Appendix A – Economic allocation

12.1 Cradle-to-gate LCI results – Economic Allocation

Table 24 summarizes the gate-to-gate flows of material and energy crossing the system boundary of hardboard. Under materials, wood feedstocks include wood material arriving at the production facilities either in roundwood form or already either fully or partially processed into wood residues. Roundwood in log form makes up 18.9 percent of the total hardboard feedstock on average for North America. Hardboard electricity consumed onsite is 654 kWh/m^3. On-site water usage for ground water and cooling water was 10,033 L/m^3, allocated. By far, cooling water was the highest representing 97 percent of the water consumed. Water recycling onsite was 69 percent leaving a net water consumption at 3,110 L/m^3, allocated.

Hardboard production air emission data were collected from surveyed mill data and augmented by secondary resources (USEPA 2002; Santos et al. 2007). The main emission sources outside of boilers are digesters/refiners, mat formers, hot presses, dryers, tempering ovens, humidification kilns, and sanding/finishing operations. Baghouses are the primary collectors of particulate matter with all four surveyed mills using the emission control device (ECD). To reduce VOC emissions from dryers and refiners, mills reported the use of regenerative thermal oxidizers (RTO), wet scrubbers, or biofiltration systems. RTO are designed to destroy VOCs and other emissions including PM and soot (USEPA 2003a). The bio-filtration system, similar to a wet scrubber, also captures nitrous oxides, carbon monoxide, and other organic compounds such as formaldehyde (USEPA 2002).

If not reported in surveys, air emissions were derived from emission data categorized by the U.S. Environmental Protection Agency (USEPA 2002; USEPA 2003a; USEPA 2003b; USEPA 2003c; USEPA 2003d; DEQ 2006a; 2006b; Santos et al. 2007).

Table 24 Unit process inputs/outputs to produce 1 m^3 of hardboard, North American average, unallocated (economic allocation)

Products	Value	Unit/m^3	Allocation (%)
Hardboard/Engineered wood siding and trim	1.0	m^3	100%
Bag house dust, wood fuel	46.7	kg	
Culled boards, wood fuel	33.8	kg	
Sander dust, wood fuel	18.7	kg	
Dry sawdust, wood fuel	5.9	kg	
Bag house dust, re-pulped	1.4	kg	
Other, not specified	15.0	kg	
Resources	**Value**	**Unit/m3**	
Water, well, in ground	303	L	
Water, cooling, surface	11,323	L	
Materials/fuels	**Value**	**Unit/m3**	
Wood feedstock, average North America, oven-dried	844	kg	
Phenol-formaldehyde (PF) resin	15.3	kg	
Paraffin Emulsion (Wax)	13.6	kg	
Zinc Borate	6.92	kg	
Alum	5.09	kg	
Compregnite	4.18	kg	
Release agent	0.456	kg	

Slack Wax	0.306	kg	
Linseed oil	0.086	kg	
Electricity, at Grid	654	kWh	
Diesel, combusted in industrial equipment	3.56	L	
Gasoline, combusted in equipment	0.15	L	
LPG, combusted in industrial equipment	7.96	L	
Natural gas, combusted in industrial boiler	7.90	m^3	
Wood fuel, combusted in boiler, self-generated	318	kg	
Wood fuel, combusted in boiler, purchased	290	kg	
Residual fuel oil, combusted in industrial boiler	12	L	
Transport, combination truck, diesel power, purchased wood fuel	3.2	tkm	
Transport, combination truck, diesel power, wood feedstock	56.6	tkm	
Transport, combination truck, diesel powered, PF resin	5.76	tkm	
Transport, combination truck, diesel powered, paraffin wax	8.05	tkm	
Transport, combination truck, diesel powered, zinc borate	0.75	tkm	
Transport, combination truck, diesel powered, alum	1.20	tkm	
Transport, combination truck, diesel powered, Compregnite	0.45	tkm	
Transport, combination truck, diesel powered, release agent	0.05	tkm	
Transport, combination truck, diesel powered, slack wax	0.02	tkm	
Transport, combination truck, diesel powered, landfill waste	2.13	tkm	
Transport, combination truck, diesel powered, linseed oil	0.00	tkm	
Hydraulic fluid	0.38	kg	
Greases	0.04	kg	
Motor oil	0.02	kg	
Potable water	10.3	L	
Paint	8.99	L	
Ink	0.006	kg	
Wrapping material - Packaging	0.494	kg	
Strap Protectors - Packaging	1.42	kg	
Strapping - Packaging	0.330	kg	
Runners - Packaging	6.97	kg	
Emissions to air	**Value**	**Unit/m3**	**Comments**
Acetaldehyde	5.30E-02	kg	Primary
Acetone	1.74E-02	kg	
Acrolein	2.30E-02	kg	Primary
Alpha-pinene	8.08E-06	kg	
Benzene	3.57E-05	kg	Primary
Beta-pinene	1.31E-05	kg	
Carbon monoxide	2.06E-01	kg	
Chloroethane (Ethane, chloro-)	1.81E-05	kg	
Chloromethane (Methane, monochloro-,R-40)	1.71E-04	kg	
Cresols	7.71E-04	kg	
Cumene	0.00E+00	kg	
Ethylbenzene (Benzene, ethyl)	4.57E-05	kg	
Formaldehyde	6.93E-02	kg	Primary
Formic acid	7.85E-02	kg	Primary
Hexaldehyde (hexanal)	1.69E-02	kg	
Lead	0.00E+00	kg	
Limonene	7.24E-04	kg	
Mercury	0.00E+00	kg	
Methanol	3.08E-01	kg	Primary
Methyl ethyl ketone	3.41E-03	kg	
Methyl isobutyl ketone	7.85E-03	kg	

Nitroux oxide	4.00E-03	kg	
NMVOC, unspecified origin[b]	0.00E+00	kg	
PM2.5	0.00E+00	kg	
PM10	8.91E-02	kg	
Particulates, > 2.5 um, and < 10um	8.91E-02	kg	
Particulates, unspecified	1.47E-01	kg	
Phenol	9.42E-02	kg	Primary
Propionaldehyde (propanal)	1.79E-01	kg	Primary
Styrene	0.00E+00	kg	
Sulfur dioxide	3.07E-01	kg	Primary
Toluene	1.85E-03	kg	
Total hydrocarbons	1.99E+00	kg	
VOC, volatile organic compounds	1.40E+00	kg	Primary
Xylenes	7.66E-05	kg	
Emissions to water	**Value**	**Unit/m3**	
BOD5, Biological Oxygen Demand	2.0	kg	Primary
COD, Chemical Oxygen Demand	7.7	kg	Primary
Suspended solids, unspecified	3.8	kg	Primary
Waste to treatment	**Value**	**Unit/m3**	
Waste to inert landfill	42.6	kg	Primary
Waste to recycling	26.5	kg	Primary

[a] Non-methane volatile organic compound

Cradle-to-gate life-cycle inventory results for hardboard are presented by three life stages, 1) forestry operations, 2) wood residue production, and 3) hardboard production (Tables 25-28). The majority of the raw material energy consumption occurs during hardboard production, followed by the production of the wood residue with only a very small portion arising from forestry operations. By mass, wood fuel at 885 kg/m^3 or 72 percent was consumed the most and consumed entirely during hardboard production as no drying of feedstock during wood residue production was performed before arriving at the hardboard plants. Wood fuel was burned onsite to generate onsite thermal energy and off-site at a sawmill facility to produce wooden runners for the final product. Coal at 195 kg/m^3 was used primarily to generate electricity represented 16 percent of the raw fuel consumed.

Table 25 Raw material consumption for energy production per 1 m^3 of hardboard, North American average (economic allocation).

	Forest operations	Residue production	Hardboard production	Total	
	kg/m3				
Coal, in ground	0.34	3.58	190.97	194.89	16%
Gas, natural, in ground	0.20	0.35	46.83	47.38	4%
Oil, crude, in ground	5.17	2.59	89.58	97.34	8%
Uranium oxide, in ore	0.00	0.00	0.01	0.01	0%
Wood fuel	0.00	0.38	884.62	885.01	72%
Total	5.71	6.90	1212.01	1224.63	100%

Hardboard manufacturers reported onsite air emissions (Table 26) including particulate and particulate PM_{10} (less than 10 µm in size) that are emitted during refining, drying, and trimming.

Other air emissions include VOCs from drying and pressing. Fossil and biogenic CO_2 released in the production of 1 m^3 of hardboard were 696 and 1,070 kg, respectively. A complete list of all air emissions for the cradle-to-gate production of hardboard can be found in Appendix B. Boiler emissions are tracked separately and are not included in Table 26.

Table 26 Air emissions released per 1 m^3 of hardboard, North American average (economic allocation)

Substance	Forest operations	Wood residue production	Hardboard production	Total
	kg/m^3			
Acetaldehyde	6.99E-05	3.90E-05	5.38E-02	5.39E-02
Acetone	0.00E+00	0.00E+00	1.74E-02	1.74E-02
Acrolein	8.47E-06	2.37E-05	2.35E-02	2.36E-02
Aldehydes, unspecified	2.10E-04	1.07E-04	3.16E-03	3.47E-03
alpha-Pinene	0.00E+00	0.00E+00	8.08E-06	8.08E-06
Ammonia	1.06E-04	6.58E-05	1.10E-02	1.11E-02
Ammonium chloride	3.48E-07	5.28E-06	3.31E-04	3.37E-04
Benzene	8.52E-05	2.95E-05	3.37E-04	4.52E-04
Benzene, ethyl-	6.62E-12	3.29E-09	4.57E-05	4.57E-05
Beta-Pinene	0.00E+00	0.00E+00	1.31E-05	1.31E-05
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	7.05E-05	1.22E-04	1.62E-02	1.64E-02
Carbon dioxide	0.00E+00	8.85E-04	2.26E-01	2.27E-01
Carbon dioxide, biogenic	1.57E-02	1.68E+00	1.07E+03	1.07E+03
Carbon dioxide, fossil	1.68E+01	1.62E+01	6.63E+02	6.96E+02
Carbon monoxide	3.44E-06	3.20E-03	9.68E-01	9.71E-01
Carbon monoxide, biogenic	0.00E+00	8.89E-04	1.93E+00	1.93E+00
Carbon monoxide, fossil	1.45E-01	5.39E-02	1.22E+00	1.42E+00
Cresol	0.00E+00	0.00E+00	7.71E-04	7.71E-04
Dinitrogen monoxide	1.33E-05	1.99E-04	1.20E-02	1.22E-02
Ethane, chloro-	2.96E-12	3.37E-11	1.81E-05	1.81E-05
Formaldehyde	1.08E-04	3.58E-05	1.03E-01	1.03E-01
Formic acid	0.00E+00	0.00E+00	7.85E-02	7.85E-02
HAPs	0.00E+00	1.72E-06	3.75E-03	3.76E-03
Hexanal	0.00E+00	0.00E+00	1.59E-02	1.59E-02
Hydrocarbons, unspecified	2.01E-06	3.05E-05	1.99E+00	1.99E+00
Hydrogen chloride	1.90E-04	1.97E-03	1.04E-01	1.06E-01
Hydrogen fluoride	2.24E-05	2.32E-04	1.23E-02	1.26E-02
Isoprene	3.95E-04	4.24E-03	2.95E-01	3.00E-01
Kerosene	1.67E-07	2.53E-06	1.59E-04	1.61E-04
Lead	8.99E-08	9.78E-07	1.49E-04	1.50E-04
Limonene	0.00E+00	0.00E+00	7.24E-04	7.24E-04
Magnesium	1.64E-06	1.70E-05	9.06E-04	9.25E-04
Metals, unspecified	4.47E-14	2.25E-04	2.18E-08	2.25E-04
Methane	2.19E-02	2.59E-02	1.55E+00	1.60E+00
Methane, biogenic	0.00E+00	6.11E-06	1.33E-02	1.33E-02
Methane, fossil	1.55E-03	1.14E-03	1.12E-01	1.15E-01
Methane, monochloro-, R-40	3.74E-11	4.26E-10	1.71E-04	1.71E-04
Methanol	0.00E+00	3.12E-05	3.13E-01	3.13E-01
Methyl ethyl ketone	2.75E-11	3.13E-10	3.41E-03	3.41E-03
Nickel	1.33E-06	1.45E-06	4.87E-04	4.90E-04
Nitrogen oxides	3.05E-01	9.25E-02	3.15E+00	3.55E+00
NMVOC, non-methane volatile organic compounds, unspecified origin	1.02E-02	5.43E-03	1.61E-01	1.77E-01
Organic substances, unspecified	9.27E-07	1.07E-05	2.84E-03	2.85E-03
Other Organic	0.00E+00	5.79E-08	1.26E-04	1.26E-04
Particulates, < 10 um	0.00E+00	1.33E-04	3.71E-01	3.71E-01
Particulates, < 2.5 um	0.00E+00	2.84E-04	8.54E-02	8.57E-02
Particulates, > 10 um	0.00E+00	6.17E-04	2.85E-03	3.47E-03
Particulates, > 2.5 um, and < 10um	9.39E-03	4.47E-03	4.89E-02	6.28E-02
Particulates, unspecified	1.69E-03	1.42E-01	2.53E+00	2.67E+00
Phenol	1.13E-12	2.41E-07	1.20E-01	1.20E-01
Propanal	2.68E-11	2.61E-07	5.30E-02	5.30E-02
Propene	2.35E-04	1.40E-05	1.90E-04	4.39E-04
Radionuclides (Including Radon)	9.33E-06	1.41E-04	8.87E-03	9.03E-03
Selenium	2.07E-07	2.04E-06	1.12E-04	1.14E-04
Sulfur dioxide	9.42E-03	5.63E-02	4.04E+00	4.10E+00
Sulfur monoxide	1.69E-02	8.74E-03	4.31E-01	4.56E-01
Sulfur oxides	0.00E+00	1.58E-04	3.68E-02	3.69E-02
Toluene	3.73E-05	2.23E-06	1.88E-03	1.92E-03
VOC, volatile organic compounds	7.99E-03	4.34E-03	2.00E+00	2.01E+00

Substance	Forest operations	Wood residue production	Hardboard production	Total
Wood (dust)	0.00E+00	4.14E-04	3.37E-01	3.37E-01
Xylene	2.60E-05	1.55E-06	9.77E-05	1.25E-04

Waterborne emissions produced are shown in Table 27. Suspended solids, with a value of 29.1 kg/m^3 and chloride at 19.6 kg/m^3 were two largest water emitters. For suspended solids, most of this was a result of crude oil production and natural gas extraction followed by onsite hardboard production itself. Most of chloride emission was from producing PF resin and alum used to form the panels and thus did not occur at the production facilities.

Table 27 Emissions to water released per 1 m^3 of hardboard, North American average (economic allocation).

Substance	Forest operations	Wood residue production	Hardboard production	Total
Acidity, unspecified	0.00E+00	1.82E-14	1.73E-03	1.73E-03
Acids, unspecified	2.53E-10	5.57E-09	3.68E-04	3.68E-04
Aluminium	1.67E-03	8.95E-04	3.39E-02	3.65E-02
Ammonia	3.61E-04	1.97E-04	8.49E-03	9.05E-03
Ammonium, ion	7.45E-08	-1.64E-06	5.41E-04	5.39E-04
Arsenic	5.28E-06	2.93E-06	1.32E-04	1.41E-04
Barium	2.28E-02	1.17E-02	4.33E-01	4.68E-01
Benzene	3.23E-05	1.84E-05	8.59E-04	9.09E-04
Benzoic acid	1.95E-05	1.09E-05	5.20E-04	5.50E-04
BOD5, Biological Oxygen Demand	3.52E-03	1.22E-02	2.10E+00	2.12E+00
Boron	6.05E-05	3.38E-05	1.61E-03	1.70E-03
Bromide	4.13E-03	2.31E-03	1.10E-01	1.16E-01
Calcium	6.19E-02	3.46E-02	1.65E+00	1.74E+00
Chloride	6.96E-01	3.89E-01	1.85E+01	1.96E+01
Chromium	4.39E-05	2.20E-05	7.29E-04	7.95E-04
Chromium III	3.31E-06	2.19E-06	1.45E-04	1.50E-04
COD, Chemical Oxygen Demand	6.69E-03	3.68E-03	7.84E+00	7.85E+00
Copper	5.49E-06	3.92E-06	1.84E-04	1.94E-04
Detergent, oil	1.62E-05	9.22E-06	4.60E-04	4.86E-04
Fluoride	1.21E-06	4.08E-05	1.17E-03	1.21E-03
Hexanoic acid	4.05E-06	2.26E-06	1.08E-04	1.14E-04
Iron	3.32E-03	1.82E-03	7.19E-02	7.71E-02
Lead	1.11E-05	6.09E-06	2.57E-04	2.74E-04
Lithium	9.93E-04	1.69E-03	2.24E-01	2.26E-01
Magnesium	1.21E-02	6.76E-03	3.22E-01	3.41E-01
Manganese	2.17E-05	4.12E-05	2.25E-03	2.32E-03
Nickel	5.21E-06	2.81E-06	1.20E-04	1.28E-04
Nitrogen, total	1.85E-07	2.99E-06	2.55E-04	2.58E-04
Oils, unspecified	4.45E-04	2.55E-04	1.19E-02	1.26E-02
Organic compounds (dissolved)	0.00E+00	0.00E+00	2.22E-04	2.22E-04
Phenol	8.18E-06	4.10E-06	1.38E-04	1.50E-04
Phenols, unspecified	1.55E-06	1.28E-06	1.09E-04	1.12E-04
Phosphate	0.00E+00	1.68E-05	1.36E-04	1.53E-04
Silver	4.05E-05	2.26E-05	1.07E-03	1.14E-03
Sodium	1.96E-01	1.10E-01	5.22E+00	5.52E+00
Solved substances, inorganic	0.00E+00	0.00E+00	2.95E-04	2.95E-04
Strontium	1.05E-03	5.87E-04	2.79E-02	2.96E-02
Sulfate	1.55E-03	3.07E-03	1.81E-01	1.86E-01
Sulfide	9.49E-07	9.69E-07	2.09E-04	2.10E-04
Sulfur	5.10E-05	2.85E-05	1.36E-03	1.44E-03
Suspended solids, unspecified	9.09E-01	5.06E-01	2.76E+01	2.91E+01
Titanium	1.60E-05	8.19E-06	2.98E-04	3.22E-04
Toluene	3.05E-05	1.71E-05	8.12E-04	8.60E-04
Waste water/m3	0.00E+00	6.40E+00	2.88E+00	9.28E+00
Water	0.00E+00	2.38E+00	0.00E+00	2.38E+00
Xylene	1.64E-05	9.13E-06	4.30E-04	4.56E-04
Zinc	3.85E-05	2.15E-05	8.44E-04	9.04E-04

Solid emissions include ash generated onsite from the boiler and in the upstream processes, primarily fuels and resins, used in hardboard production (Table 28). A total of 165 kg/m^3 solid waste was generated with 45 percent generated onsite of which 36 percent of this was recycled. Hardboard production sent a total of 46.86 kg or 51 percent of the solid waste generated to landfill.

Table 28. Waste to treatment per 1 m^3 of hardboard, North American average (economic allocation)

Waste to treatment	Forest operations	Wood residue production	Hardboard production	Total
	kg/m3			
Waste disposal, onsite	0.04	0.32	46.50	46.86
Waste to recycling, onsite	0.00	0.05	26.50	26.55
Waste disposal, upstream	0.24	1.91	89.24	91.39
Total	0.28	2.28	162.24	164.8

12.2 Life-cycle impact assessment results

Environmental performance results for global warming potential (GWP), acidification, eutrophication, ozone depletion and smog, energy consumption from non-renewables, renewables, wind, hydro, solar, and nuclear fuels, renewable and nonrenewable resources, and solid waste are shown in Table 29. For GWP, 95 percent of the CO_2 eq. emissions, 709 kg CO_2 eq., come from producing hardboard. Similar results are presented for acidification, eutrophication, and smog, representing 95, 97, and 90 percent contributed from hardboard production, respectively.

Renewable-biomass fuel, at 18.5 GJ, represented the greatest proportion of energy consumed (57%) for total cradle to gate primary energy use. Non-renewable fossil fuels and non-renewable nuclear represented 36 and 7 percent of the total primary energy, respectively. Of the three life cycle stages considered in this study, hardboard production consumes 98 percent of the total primary energy consumption. Overall, the manufacture of hardboard in North America over 58 percent energy self-sufficient with its use of renewable biomass. Water intake is high for the cradle-to-gate production of hardboard at over 10,000 L/m^3. While this number is high, 69 percent of this usage is recycled, resulting in a net water consumption of 3,129 L/m^3. It is clear that water conservation measures currently in place in North American hardboard facilities have made a dramatic impact in the reduction of water consumption.

Table 29 Environmental performance of 1 m^3 hardboard, North American average (economic allocation).

Impact category	Unit	Total	Forestry operations	Wood residue production	Hardboard production
Global warming potential (GWP)	kg CO_2 eq	743.25	17.43	16.98	708.84
Acidification Potential	kg SO_2 eq	7.2186	0.2403	0.1322	6.8461
Eutrophication Potential	kg N eq	0.6653	0.0143	0.0051	0.6459
Ozone depletion Potential	kg CFC-11 eq	0.000	0.0000	0.0000	0.0000
Smog Potential	kg O_3 eq	101.06	7.60	2.36	91.10
Total Primary Energy	MJ	33,287	258	283	32,746
Non-renewable fossil	*MJ*	*12,136*	255.08	241.59	11,639
Non-renewable nuclear	*MJ*	*2,424*	2.50	37.89	2,384
Renewable (solar, wind, hydroelectric, and geothermal)	*MJ*	*207.48*	0.30	3.36	204
Renewable, biomass	*MJ*	*18,519*	0	0.42	18,518.81
Material resource consumption (Non-fuel resources)	**Unit**	**Total**	**Forestry operations**	**Wood residue production**	**Hardboard production**
Non-renewable materials	kg	5.77	0	0.01	5.76
Renewable materials	kg	679.57	0	13.92	665.65
Fresh water	L	10,094.41	0	13.41	10,081
Waste generated	**Unit**	**Total**	**Forestry operations**	**Wood residue production**	**Hardboard production**
Solid waste	kg	164.8	0.28	2.28	162.24

12.3 Carbon

Using the same method applied for mass allocation, 743 kg CO_2e were released in the production of 1 m^3 of hardboard. That same 1 m^3 of hardboard stores 364 kg of carbon[6] or 1,335 kg CO_2 eq.[7], resulting in more carbon storage in the product then released during manufacturing (cradle to gate). Total carbon impacts increased by 13 percent when an economic allocation was applied.

Table 30 Carbon per 1 m^3 hardboard, North American average (economic allocation).

	kg CO_2 equivalent
released forestry operations	17
released hardboard and residue manufacturing	726
CO_2 eq. stored in product	1,335

[6] Assuming a 50% carbon content

[7] 728 OD kg of wood in hardboard × (0.5 kg carbon/1.0 OD kg wood) × (44 kg CO_2/kmole/12 kg carbon/kmole) = 1335 kg CO_2 eq.

13 Appendix B – Life cycle inventory, full results

13.1 Air Emissions – Mass Allocation

Table 31 Air emissions released per 1 m3 of hardboard, North American average (mass allocation)

Substance	Unit	Forestry operations	Wood residue production	Hardboard production
2-Chloroacetophenone	kg	4.93E-13	5.62E-12	1.58E-09
2-Methyl-4-chlorophenoxyacetic acid	kg	0.00E+00	4.40E-16	2.41E-10
2,4-D	kg	0.00E+00	2.36E-14	1.29E-08
5-methyl Chrysene	kg	3.28E-12	3.40E-11	1.81E-09
Acenaphthene	kg	7.61E-11	7.89E-10	4.2E-08
Acenaphthylene	kg	3.73E-11	3.87E-10	2.06E-08
Acetaldehyde	kg	6.99E-05	3.90E-05	0.053787
Acetochlor	kg	0.00E+00	3.27E-13	1.79E-07
Acetone	kg	0.00E+00	0.00E+00	0.0174
Acetophenone	kg	1.06E-12	1.21E-11	3.39E-09
Acrolein	kg	8.47E-06	2.37E-05	0.023529
Alachlor	kg	0.00E+00	3.22E-14	1.76E-08
Aldehydes, unspecified	kg	2.10E-04	1.07E-04	0.003156
alpha-Pinene	kg	0.00E+00	0.00E+00	8.08E-06
Ammonia	kg	1.06E-04	6.58E-05	0.010976
Ammonium chloride	kg	3.48E-07	5.28E-06	0.000331
Anthracene	kg	3.13E-11	3.25E-10	1.73E-08
Antimony	kg	2.69E-09	6.95E-08	1.48E-06
Arsenic	kg	8.27E-08	7.67E-07	4.14E-05
Atrazine	kg	0.00E+00	6.37E-13	3.49E-07
Barium	kg	0.00E+00	4.99E-10	1.39E-09
Bentazone	kg	0.00E+00	2.60E-15	1.43E-09
Benzene	kg	8.52E-05	2.95E-05	0.000337
Benzene, chloro-	kg	1.55E-12	1.77E-11	4.97E-09
Benzene, ethyl-	kg	6.62E-12	3.29E-09	4.57E-05
Benzo(a)anthracene	kg	1.19E-11	1.24E-10	6.59E-09
Benzo(a)pyrene	kg	5.67E-12	5.88E-11	3.13E-09
Benzo(b,j,k)fluoranthene	kg	1.64E-11	1.70E-10	9.06E-09
Benzo(g,h,i)perylene	kg	4.03E-12	4.17E-11	2.22E-09
Benzo(ghi)perylene	kg	0.00E+00	2.91E-16	7.45E-16
Benzyl chloride	kg	4.93E-11	5.62E-10	1.58E-07
Beryllium	kg	4.08E-09	4.07E-08	2.07E-06
Beta-Pinene	kg	0.00E+00	0.00E+00	1.31E-05
Biphenyl	kg	2.54E-10	2.63E-09	1.4E-07
Bromoform	kg	2.75E-12	3.13E-11	8.82E-09
Bromoxynil	kg	0.00E+00	5.70E-15	3.12E-09
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	kg	7.05E-05	1.22E-04	0.016166
Butadiene	kg	3.56E-06	2.11E-07	2.88E-06
Cadmium	kg	1.90E-08	1.15E-07	7.48E-06
Carbofuran	kg	0.00E+00	4.87E-15	2.67E-09
Carbon dioxide	kg	0.00E+00	8.85E-04	0.22642
Carbon dioxide, biogenic	kg	1.57E-02	1.68E+00	1066.727
Carbon dioxide, fossil	kg	1.68E+01	1.62E+01	663.1953
Carbon disulfide	kg	9.16E-12	1.04E-10	1.44E-07
Carbon monoxide	kg	3.44E-06	3.20E-03	0.967972
Carbon monoxide, biogenic	kg	0.00E+00	8.89E-04	1.931895

Carbon monoxide, fossil	kg	1.45E-01	5.39E-02	1.221236
Chloride	kg	1.20E-11	1.29E-10	9.01E-09
Chlorinated fluorocarbons and hydrochlorinated fluorocarbons, unspecified	kg	0.00E+00	6.32E-11	6.08E-08
Chlorine	kg	0.00E+00	4.16E-06	3.91E-08
Chloroform	kg	4.16E-12	4.74E-11	1.33E-08
Chlorpyrifos	kg	0.00E+00	3.75E-14	2.06E-08
Chromium	kg	5.83E-08	5.34E-07	2.74E-05
Chromium VI	kg	1.18E-08	1.22E-07	6.51E-06
Chrysene	kg	1.49E-11	1.55E-10	8.24E-09
Cobalt	kg	1.06E-07	2.48E-07	4.12E-05
Copper	kg	9.49E-10	4.16E-09	3.54E-07
Cresol	kg	0.00E+00	0.00E+00	0.000771
Cumene	kg	3.74E-13	1.86E-07	1.37E-07
Cyanazine	kg	0.00E+00	5.62E-15	3.08E-09
Cyanide	kg	1.76E-10	2.01E-09	5.65E-07
Dicamba	kg	0.00E+00	3.31E-14	1.81E-08
Dimethenamid	kg	0.00E+00	7.82E-14	4.29E-08
Dimethyl ether	kg	0.00E+00	1.35E-09	9.84E-10
Dinitrogen monoxide	kg	1.33E-05	1.99E-04	0.011983
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg	3.51E-13	8.78E-09	1.53E-10
Dioxins (unspec.)	kg	0.00E+00	0.00E+00	6.34E-15
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	0.00E+00	8.33E-22	1.61E-21
Dipropylthiocarbamic acid S-ethyl ester	kg	0.00E+00	5.35E-14	2.94E-08
Ethane, 1,1,1-trichloro-, HCFC-140	kg	4.86E-10	2.59E-10	1.12E-08
Ethane, 1,2-dibromo-	kg	8.46E-14	9.77E-13	2.72E-10
Ethane, 1,2-dichloro-	kg	2.82E-12	3.21E-11	9.04E-09
Ethane, chloro-	kg	2.96E-12	3.37E-11	1.81E-05
Ethene, tetrachloro-	kg	7.58E-09	6.76E-08	3.96E-06
Ethene, trichloro-	kg	0.00E+00	1.01E-12	7.07E-11
Ethylene oxide	kg	0.00E+00	8.38E-10	4.86E-08
Fluoranthene	kg	1.06E-10	1.10E-09	5.85E-08
Fluorene	kg	1.36E-10	1.41E-09	7.5E-08
Fluoride	kg	1.10E-08	1.65E-07	1.76E-05
Formaldehyde	kg	1.08E-04	3.58E-05	0.103048
Formic acid	kg	0.00E+00	0.00E+00	0.0785
Furan	kg	6.91E-13	7.65E-12	4.06E-10
Glyphosate	kg	0.00E+00	7.03E-14	3.85E-08
HAPs	kg	0.00E+00	1.72E-06	0.003754
HAPS, unspecified	kg	0.00E+00	2.96E-07	0
Heat, waste	MJ	0.00E+00	1.19E-03	4.405602
Hexanal	kg	0.00E+00	0.00E+00	0.0159
Hexane	kg	4.72E-12	5.38E-11	2.79E-07
Hydrazine, methyl-	kg	1.20E-11	1.37E-10	3.84E-08
Hydrocarbons, unspecified	kg	2.01E-06	3.05E-05	1.991914
Hydrogen	kg	0.00E+00	4.28E-10	3.05E-07
Hydrogen chloride	kg	1.90E-04	1.97E-03	0.103528
Hydrogen fluoride	kg	2.24E-05	2.32E-04	0.012345
Hydrogen sulfide	kg	3.89E-13	4.18E-12	2.91E-10
Indeno(1,2,3-cd)pyrene	kg	9.10E-12	9.43E-11	5.02E-09
Iron	kg	0.00E+00	4.99E-10	9.64E-10
Isophorone	kg	4.09E-11	4.66E-10	1.31E-07
Isoprene	kg	3.95E-04	4.24E-03	0.295177
Kerosene	kg	1.67E-07	2.53E-06	0.000159
Lead	kg	8.99E-08	9.78E-07	0.000149
Limonene	kg	0.00E+00	0.00E+00	0.000724
Magnesium	kg	1.64E-06	1.70E-05	0.000906
Manganese	kg	1.21E-07	9.23E-06	5.89E-05
Mercaptans, unspecified	kg	1.45E-08	1.74E-07	4.9E-05

Mercury	kg	1.58E-08	1.53E-07	9.3E-06
Metals, unspecified	kg	4.47E-14	2.25E-04	2.18E-08
Methane	kg	2.19E-02	2.59E-02	1.550027
Methane, biogenic	kg	0.00E+00	6.11E-06	0.013328
Methane, bromo-, Halon 1001	kg	1.13E-11	1.29E-10	3.62E-08
Methane, chlorodifluoro-, HCFC-22	kg	0.00E+00	6.97E-15	4.04E-13
Methane, chlorotrifluoro-, CFC-13	kg	0.00E+00	6.61E-14	3.84E-12
Methane, dichloro-, HCC-30	kg	1.21E-07	2.05E-06	5.22E-05
Methane, dichlorodifluoro-, CFC-12	kg	5.99E-10	3.00E-10	8.28E-09
Methane, fossil	kg	1.55E-03	1.14E-03	0.112012
Methane, monochloro-, R-40	kg	3.74E-11	4.26E-10	0.000171
Methane, tetrachloro-, CFC-10	kg	5.99E-11	2.37E-07	2.15E-09
Methanol	kg	0.00E+00	3.12E-05	0.313395
Methyl ethyl ketone	kg	2.75E-11	3.13E-10	0.00341
Methyl methacrylate	kg	1.41E-12	1.61E-11	4.52E-09
Metolachlor	kg	0.00E+00	2.58E-13	1.42E-07
Metribuzin	kg	0.00E+00	1.20E-15	6.56E-10
N-Nitrodimethylamine	kg	0.00E+00	2.25E-13	1.58E-11
Naphthalene	kg	2.18E-08	5.63E-07	4.23E-05
Nickel	kg	1.33E-06	1.45E-06	0.000487
Nitrogen oxides	kg	3.05E-01	9.25E-02	3.154067
Nitrogen, total	kg	0.00E+00	1.76E-07	1.46E-07
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1.02E-02	5.43E-03	0.161001
Organic acids	kg	1.28E-09	1.94E-08	1.22E-06
Organic substances, unspecified	kg	9.27E-07	1.07E-05	0.002836
Other Organic	kg	0.00E+00	5.79E-08	0.000126
PAH, polycyclic aromatic hydrocarbons	kg	1.53E-05	9.08E-07	1.24E-05
Paraquat	kg	0.00E+00	5.23E-15	2.87E-09
Parathion, methyl	kg	0.00E+00	3.95E-15	2.17E-09
Particulates	kg	0.00E+00	6.59E-10	4.81E-10
Particulates, < 10 um	kg	0.00E+00	1.33E-04	0.371093
Particulates, < 2.5 um	kg	0.00E+00	2.84E-04	0.085375
Particulates, > 10 um	kg	0.00E+00	6.17E-04	0.002853
Particulates, > 2.5 um, and < 10um	kg	9.39E-03	4.47E-03	0.048911
Particulates, unspecified	kg	1.69E-03	1.42E-01	2.525637
Pendimethalin	kg	0.00E+00	2.69E-14	1.47E-08
Permethrin	kg	0.00E+00	2.41E-15	1.32E-09
Phenanthrene	kg	4.03E-10	4.17E-09	2.22E-07
Phenol	kg	1.13E-12	2.41E-07	0.120301
Phenols, unspecified	kg	6.12E-08	3.46E-07	2.26E-05
Phorate	kg	0.00E+00	1.24E-15	6.79E-10
Phosphate	kg	0.00E+00	4.02E-09	2.93E-09
Phthalate, dioctyl-	kg	5.14E-12	5.86E-11	1.65E-08
Polycyclic organic matter, unspecified	kg	0.00E+00	1.68E-13	9.77E-12
Potassium	kg	0.00E+00	8.85E-08	1.71E-07
Propanal	kg	2.68E-11	2.61E-07	0.053033
Propene	kg	2.35E-04	1.40E-05	0.00019
Propylene oxide	kg	0.00E+00	2.80E-09	1.62E-08
Pyrene	kg	4.92E-11	5.10E-10	2.72E-08
Radioactive species, unspecified	Bq	8.45E+03	8.75E+04	4652962
Radionuclides (Including Radon)	kg	9.33E-06	1.41E-04	0.008875
Selenium	kg	2.07E-07	2.04E-06	0.000112
Simazine	kg	0.00E+00	1.70E-14	9.3E-09
Sodium	kg	0.00E+00	2.04E-09	3.94E-09
Styrene	kg	1.76E-12	2.01E-11	5.65E-09
Sulfur	kg	0.00E+00	7.94E-11	3.9E-05
Sulfur dioxide	kg	9.42E-03	5.63E-02	4.039151
Sulfur monoxide	kg	1.69E-02	8.74E-03	0.430812

Sulfur oxides	kg	0.00E+00	1.58E-04	0.036752
Sulfur, total reduced	kg	0.00E+00	6.31E-09	1.22E-08
Sulfuric acid, dimethyl ester	kg	3.38E-12	3.86E-11	1.09E-08
t-Butyl methyl ether	kg	2.47E-12	2.81E-11	7.91E-09
Tar	kg	1.36E-11	1.45E-10	1.01E-08
Terbufos	kg	0.00E+00	4.22E-14	2.32E-08
TOC, Total Organic Carbon	kg	0.00E+00	2.15E-05	1.95E-09
Toluene	kg	3.73E-05	2.23E-06	0.00188
Toluene, 2,4-dinitro-	kg	1.97E-14	2.25E-13	6.33E-11
Trichloroethane	kg	0.00E+00	0.00E+00	3.6E-08
Vinyl acetate	kg	5.36E-13	6.11E-12	1.72E-09
VOC, volatile organic compounds	kg	7.99E-03	4.34E-03	1.998712
Wood (dust)	kg	0.00E+00	4.14E-04	0.336957
Xylene	kg	2.60E-05	1.55E-06	9.77E-05
Zinc	kg	6.33E-10	6.52E-09	2.39E-07

13.2 Water Emissions – Mass Allocation

Table 32 Water emissions released per 1 m3 of hardboard, North American average (mass allocation)

Substance		Forest operations	Wood residue production	Hardboard production
2-Hexanone	kg	1.26E-07	9.79E-08	2.89E-06
2-Methyl-4-chlorophenoxyacetic acid	kg	0.00E+00	7.45E-17	8.92E-12
2-Propanol	kg	0.00E+00	2.35E-11	5.12E-09
2,4-D	kg	0.00E+00	4.00E-15	4.78E-10
4-Methyl-2-pentanone	kg	8.10E-08	6.30E-08	1.86E-06
Acetaldehyde	kg	0.00E+00	3.29E-09	4.41E-08
Acetochlor	kg	0.00E+00	5.54E-14	6.63E-09
Acetone	kg	1.93E-07	1.50E-07	4.42E-06
Acidity, unspecified	kg	0.00E+00	7.69E-14	1.49E-03
Acids, unspecified	kg	2.53E-10	1.74E-08	3.17E-04
Alachlor	kg	0.00E+00	5.45E-15	6.53E-10
Aluminium	kg	1.67E-03	1.20E-03	2.93E-02
Aluminum	kg	0.00E+00	9.47E-08	3.75E-08
Ammonia	kg	3.61E-04	2.69E-04	7.33E-03
Ammonia, as N	kg	1.27E-10	3.06E-09	8.20E-08
Ammonium, ion	kg	7.45E-08	-9.29E-06	4.67E-04
Antimony	kg	1.04E-06	6.92E-07	1.67E-05
Arsenic	kg	5.28E-06	4.06E-06	1.14E-04
Arsenic, ion	kg	0.00E+00	2.89E-11	1.31E-11
Atrazine	kg	0.00E+00	1.08E-13	1.29E-08
Barium	kg	2.28E-02	1.53E-02	3.74E-01
Bentazone	kg	0.00E+00	4.40E-16	5.27E-11
Benzene	kg	3.23E-05	2.57E-05	7.41E-04
Benzene, 1-methyl-4-(1-methylethyl)-	kg	1.93E-09	1.50E-09	4.42E-08
Benzene, ethyl-	kg	1.82E-06	1.41E-06	4.17E-05
Benzene, pentamethyl-	kg	1.44E-09	1.12E-09	3.31E-08
Benzenes, alkylated, unspecified	kg	9.11E-07	6.07E-07	1.47E-05
Benzo(a)pyrene	kg	0.00E+00	5.92E-09	8.46E-08
Benzoic acid	kg	1.95E-05	1.52E-05	4.49E-04
Beryllium	kg	2.94E-07	2.14E-07	5.87E-06
Biphenyl	kg	5.90E-08	3.93E-08	9.55E-07
BOD5, Biological Oxygen Demand	kg	3.52E-03	2.91E-02	1.81E+00
Boron	kg	6.05E-05	4.70E-05	1.39E-03
Bromide	kg	4.13E-03	3.21E-03	9.47E-02
Bromoxynil	kg	0.00E+00	5.82E-16	6.97E-11
Cadmium	kg	7.80E-07	6.28E-07	1.74E-05
Cadmium, ion	kg	0.00E+00	4.79E-12	2.18E-12
Calcium	kg	6.19E-02	4.81E-02	1.42E+00
Calcium, ion	kg	0.00E+00	3.81E-07	1.76E-07
Carbofuran	kg	0.00E+00	8.25E-16	9.88E-11
CFCs, unspecified	kg	0.00E+00	2.35E-11	5.12E-09
Chloride	kg	6.96E-01	5.41E-01	1.60E+01
Chlorpyrifos	kg	0.00E+00	6.35E-15	7.60E-10
Chromate	kg	0.00E+00	3.94E-12	5.63E-11
Chromium	kg	4.39E-05	2.81E-05	6.29E-04
Chromium III	kg	3.31E-06	3.40E-06	1.25E-04
Chromium VI	kg	1.85E-07	1.18E-07	2.20E-06
Chromium, ion	kg	0.00E+00	4.85E-11	2.42E-11
Cobalt	kg	4.27E-07	3.32E-07	9.80E-06

COD, Chemical Oxygen Demand	kg	6.69E-03	5.08E-03	6.77E+00
Copper	kg	5.49E-06	6.19E-06	1.59E-04
Copper, ion	kg	0.00E+00	4.78E-11	2.30E-11
Cumene	kg	0.00E+00	9.69E-07	2.09E-07
Cyanazine	kg	0.00E+00	9.52E-16	1.14E-10
Cyanide	kg	1.39E-09	6.78E-07	9.70E-06
Decane	kg	5.62E-07	4.37E-07	1.29E-05
Detergent, oil	kg	1.62E-05	1.30E-05	3.97E-04
Dibenzofuran	kg	3.66E-09	2.85E-09	8.40E-08
Dibenzothiophene	kg	3.15E-09	2.43E-09	7.10E-08
Dicamba	kg	0.00E+00	5.61E-15	6.71E-10
Dimethenamid	kg	0.00E+00	1.32E-14	1.59E-09
Dipropylthiocarbamic acid S-ethyl ester	kg	0.00E+00	5.47E-15	6.55E-10
Disulfoton	kg	0.00E+00	3.27E-16	3.91E-11
Diuron	kg	0.00E+00	9.18E-17	1.10E-11
DOC, Dissolved Organic Carbon	kg	7.77E-13	1.79E-06	3.86E-07
Docosane	kg	2.06E-08	1.60E-08	4.73E-07
Dodecane	kg	1.07E-06	8.29E-07	2.45E-05
Eicosane	kg	2.93E-07	2.28E-07	6.73E-06
Fluorene	kg	0.00E+00	6.15E-14	8.25E-13
Fluorene, 1-methyl-	kg	2.19E-09	1.71E-09	5.03E-08
Fluorenes, alkylated, unspecified	kg	5.28E-08	3.52E-08	8.55E-07
Fluoride	kg	1.21E-06	8.98E-05	1.01E-03
Fluorine	kg	2.61E-08	1.75E-08	4.33E-07
Furan	kg	0.00E+00	8.61E-13	1.88E-10
Glyphosate	kg	0.00E+00	1.19E-14	1.43E-09
Hexadecane	kg	1.16E-06	9.05E-07	2.67E-05
Hexanoic acid	kg	4.05E-06	3.15E-06	9.29E-05
Hydrocarbons, unspecified	kg	9.72E-13	8.84E-10	1.88E-07
Iron	kg	3.32E-03	2.48E-03	6.21E-02
Lead	kg	1.11E-05	8.40E-06	2.22E-04
Lead-210/kg	kg	2.00E-15	1.56E-15	4.59E-14
Lithium	kg	9.93E-04	3.55E-03	1.93E-01
Lithium, ion	kg	0.00E+00	9.20E-08	4.81E-08
m-Xylene	kg	5.84E-07	4.54E-07	1.34E-05
Magnesium	kg	1.21E-02	9.41E-03	2.78E-01
Manganese	kg	2.17E-05	8.35E-05	1.95E-03
Mercury	kg	1.83E-08	1.57E-08	3.73E-07
Metallic ions, unspecified	kg	1.19E-11	1.93E-09	4.04E-08
Methane, monochloro-, R-40	kg	7.76E-10	6.03E-10	1.78E-08
Methyl ethyl ketone	kg	1.55E-09	1.21E-09	3.56E-08
Metolachlor	kg	0.00E+00	4.38E-14	5.24E-09
Metribuzin	kg	0.00E+00	2.03E-16	2.43E-11
Molybdenum	kg	4.43E-07	3.44E-07	1.02E-05
n-Hexacosane	kg	1.29E-08	1.00E-08	2.95E-07
Naphthalene	kg	3.51E-07	2.28E-07	7.40E-06
Naphthalene, 2-methyl-	kg	3.05E-07	2.37E-07	7.00E-06
Naphthalenes, alkylated, unspecified	kg	1.49E-08	9.95E-09	2.42E-07
Nickel	kg	5.21E-06	3.80E-06	1.04E-04
Nickel, ion	kg	0.00E+00	5.16E-16	3.04E-16
Nitrate	kg	8.52E-14	1.09E-09	1.39E-06
Nitrate compounds	kg	3.43E-12	8.26E-11	2.21E-09
Nitric acid	kg	7.69E-09	1.85E-07	4.96E-06
Nitrogen, total	kg	1.85E-07	7.07E-06	2.20E-04
o-Cresol	kg	5.54E-07	4.31E-07	1.27E-05
o-Xylene	kg	0.00E+00	1.31E-13	4.96E-09
Octadecane	kg	2.87E-07	2.23E-07	6.59E-06
Oils, unspecified	kg	4.45E-04	3.69E-04	1.03E-02
Organic compounds (dissolved)	kg	0.00E+00	0.00E+00	1.92E-04

Organic substances, unspecified	kg	0.00E+00	1.41E-08	2.01E-07
p-Cresol	kg	5.98E-07	4.65E-07	1.37E-05
p-Xylene	kg	0.00E+00	1.31E-13	4.96E-09
Paraquat	kg	0.00E+00	8.86E-16	1.06E-10
Parathion, methyl	kg	0.00E+00	6.69E-16	8.01E-11
Pendimethalin	kg	0.00E+00	4.55E-15	5.45E-10
Permethrin	kg	0.00E+00	4.09E-16	4.90E-11
Phenanthrene	kg	5.35E-09	3.76E-09	9.82E-08
Phenanthrenes, alkylated, unspecified	kg	6.19E-09	4.13E-09	1.00E-07
Phenol	kg	8.18E-06	5.21E-06	1.19E-04
Phenol, 2,4-dimethyl-	kg	5.40E-07	4.20E-07	1.24E-05
Phenols, unspecified	kg	1.55E-06	2.21E-06	9.41E-05
Phorate	kg	0.00E+00	1.27E-16	1.51E-11
Phosphate	kg	0.00E+00	3.65E-05	1.15E-04
Phosphorus	kg	0.00E+00	1.53E-08	3.21E-05
Phosphorus compounds, unspecified	kg	0.00E+00	2.35E-12	2.81E-07
Phosphorus, total	kg	0.00E+00	2.84E-08	6.20E-06
Process solvents, unspecified	kg	0.00E+00	8.61E-11	1.88E-08
Propene	kg	0.00E+00	3.57E-07	7.69E-08
Radioactive species, Nuclides, unspecified	Bq	1.08E+01	3.68E+02	8.88E+03
Radium-226/kg	kg	6.96E-13	5.42E-13	1.60E-11
Radium-228/kg	kg	3.56E-15	2.77E-15	8.18E-14
Selenium	kg	2.28E-07	1.02E-06	2.47E-05
Silver	kg	4.05E-05	3.15E-05	9.28E-04
Simazine	kg	0.00E+00	2.87E-15	3.44E-10
Sodium	kg	1.96E-01	1.53E-01	4.50E+00
Sodium, ion	kg	0.00E+00	1.21E-06	5.57E-07
Solids, inorganic	kg	1.96E-11	4.71E-10	1.26E-08
Solved solids	kg	0.00E+00	5.45E-06	2.52E-06
Solved substances, inorganic	kg	0.00E+00	0.00E+00	2.55E-04
Strontium	kg	1.05E-03	8.17E-04	2.41E-02
Styrene	kg	0.00E+00	1.47E-13	2.41E-11
Sulfate	kg	1.55E-03	6.23E-03	1.56E-01
Sulfide	kg	9.49E-07	2.68E-06	1.80E-04
Sulfur	kg	5.10E-05	3.97E-05	1.17E-03
Sulfuric acid	kg	0.00E+00	3.07E-09	4.38E-08
Surfactants	kg	0.00E+00	6.06E-12	2.52E-07
Suspended solids, unspecified	kg	9.09E-01	7.03E-01	2.38E+01
Tar	kg	1.94E-13	4.67E-12	1.25E-10
Terbufos	kg	0.00E+00	4.32E-15	5.17E-10
Tetradecane	kg	4.67E-07	3.63E-07	1.07E-05
Thallium	kg	2.19E-07	1.46E-07	3.53E-06
Tin	kg	4.23E-06	2.99E-06	7.88E-05
Titanium	kg	1.60E-05	1.06E-05	2.57E-04
Titanium, ion	kg	0.00E+00	4.30E-11	1.62E-11
TOC, Total Organic Carbon	kg	0.00E+00	1.79E-06	6.23E-07
Toluene	kg	3.05E-05	2.38E-05	7.01E-04
Vanadium	kg	5.23E-07	4.07E-07	1.20E-05
Waste water/m3	m3	0.00E+00	1.29E-02	2.49E-03
Water	kg	0.00E+00	5.81E+00	0.00E+00
Xylene	kg	1.64E-05	1.27E-05	3.71E-04
Yttrium	kg	1.30E-07	1.01E-07	2.98E-06
Zinc	kg	3.85E-05	2.97E-05	7.28E-04
Zinc, ion	kg	0.00E+00	1.22E-09	6.02E-10

13.3 Air Emissions – Economic Allocation

Table 33 Air emissions released per 1 m3 of hardboard, North American average (economic allocation)

Substance	Unit	Forestry operations	Wood residue production	Hardboard production
2-Chloroacetophenone	kg	4.93E-13	5.62E-12	1.58E-09
2-Methyl-4-chlorophenoxyacetic acid	kg	0.00E+00	4.40E-16	2.41E-10
2,4-D	kg	0.00E+00	2.36E-14	1.29E-08
5-methyl Chrysene	kg	3.28E-12	3.40E-11	1.81E-09
Acenaphthene	kg	7.61E-11	7.89E-10	4.2E-08
Acenaphthylene	kg	3.73E-11	3.87E-10	2.06E-08
Acetaldehyde	kg	6.99E-05	3.90E-05	0.053787
Acetochlor	kg	0.00E+00	3.27E-13	1.79E-07
Acetone	kg	0.00E+00	0.00E+00	0.0174
Acetophenone	kg	1.06E-12	1.21E-11	3.39E-09
Acrolein	kg	8.47E-06	2.37E-05	0.023529
Alachlor	kg	0.00E+00	3.22E-14	1.76E-08
Aldehydes, unspecified	kg	2.10E-04	1.07E-04	0.003156
alpha-Pinene	kg	0.00E+00	0.00E+00	8.08E-06
Ammonia	kg	1.06E-04	6.58E-05	0.010976
Ammonium chloride	kg	3.48E-07	5.28E-06	0.000331
Anthracene	kg	3.13E-11	3.25E-10	1.73E-08
Antimony	kg	2.69E-09	6.95E-08	1.48E-06
Arsenic	kg	8.27E-08	7.67E-07	4.14E-05
Atrazine	kg	0.00E+00	6.37E-13	3.49E-07
Barium	kg	0.00E+00	4.99E-10	1.39E-09
Bentazone	kg	0.00E+00	2.60E-15	1.43E-09
Benzene	kg	8.52E-05	2.95E-05	0.000337
Benzene, chloro-	kg	1.55E-12	1.77E-11	4.97E-09
Benzene, ethyl-	kg	6.62E-12	3.29E-09	4.57E-05
Benzo(a)anthracene	kg	1.19E-11	1.24E-10	6.59E-09
Benzo(a)pyrene	kg	5.67E-12	5.88E-11	3.13E-09
Benzo(b,j,k)fluoranthene	kg	1.64E-11	1.70E-10	9.06E-09
Benzo(g,h,i)perylene	kg	4.03E-12	4.17E-11	2.22E-09
Benzo(ghi)perylene	kg	0.00E+00	2.91E-16	7.45E-16
Benzyl chloride	kg	4.93E-11	5.62E-10	1.58E-07
Beryllium	kg	4.08E-09	4.07E-08	2.07E-06
Beta-Pinene	kg	0.00E+00	0.00E+00	1.31E-05
Biphenyl	kg	2.54E-10	2.63E-09	1.4E-07
Bromoform	kg	2.75E-12	3.13E-11	8.82E-09
Bromoxynil	kg	0.00E+00	5.70E-15	3.12E-09
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	kg	7.05E-05	1.22E-04	0.016166
Butadiene	kg	3.56E-06	2.11E-07	2.88E-06
Cadmium	kg	1.90E-08	1.15E-07	7.48E-06
Carbofuran	kg	0.00E+00	4.87E-15	2.67E-09
Carbon dioxide	kg	0.00E+00	8.85E-04	0.22642
Carbon dioxide, biogenic	kg	1.57E-02	1.68E+00	1066.727
Carbon dioxide, fossil	kg	1.68E+01	1.62E+01	663.1953
Carbon disulfide	kg	9.16E-12	1.04E-10	1.44E-07
Carbon monoxide	kg	3.44E-06	3.20E-03	0.967972
Carbon monoxide, biogenic	kg	0.00E+00	8.89E-04	1.931895
Carbon monoxide, fossil	kg	1.45E-01	5.39E-02	1.221236
Chloride	kg	1.20E-11	1.29E-10	9.01E-09
Chlorinated fluorocarbons and hydrochlorinated fluorocarbons, unspecified	kg	0.00E+00	6.32E-11	6.08E-08

Substance	Unit	Forestry operations	Wood residue production	Hardboard production
Chlorine	kg	0.00E+00	4.16E-06	3.91E-08
Chloroform	kg	4.16E-12	4.74E-11	1.33E-08
Chlorpyrifos	kg	0.00E+00	3.75E-14	2.06E-08
Chromium	kg	5.83E-08	5.34E-07	2.74E-05
Chromium VI	kg	1.18E-08	1.22E-07	6.51E-06
Chrysene	kg	1.49E-11	1.55E-10	8.24E-09
Cobalt	kg	1.06E-07	2.48E-07	4.12E-05
Copper	kg	9.49E-10	4.16E-09	3.54E-07
Cresol	kg	0.00E+00	0.00E+00	0.000771
Cumene	kg	3.74E-13	1.86E-07	1.37E-07
Cyanazine	kg	0.00E+00	5.62E-15	3.08E-09
Cyanide	kg	1.76E-10	2.01E-09	5.65E-07
Dicamba	kg	0.00E+00	3.31E-14	1.81E-08
Dimethenamid	kg	0.00E+00	7.82E-14	4.29E-08
Dimethyl ether	kg	0.00E+00	1.35E-09	9.84E-10
Dinitrogen monoxide	kg	1.33E-05	1.99E-04	0.011983
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	kg	3.51E-13	8.78E-09	1.53E-10
Dioxins (unspec.)	kg	0.00E+00	0.00E+00	6.34E-15
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	0.00E+00	8.33E-22	1.61E-21
Dipropylthiocarbamic acid S-ethyl ester	kg	0.00E+00	5.35E-14	2.94E-08
Ethane, 1,1,1-trichloro-, HCFC-140	kg	4.86E-10	2.59E-10	1.12E-08
Ethane, 1,2-dibromo-	kg	8.46E-14	9.77E-13	2.72E-10
Ethane, 1,2-dichloro-	kg	2.82E-12	3.21E-11	9.04E-09
Ethane, chloro-	kg	2.96E-12	3.37E-11	1.81E-05
Ethene, tetrachloro-	kg	7.58E-09	6.76E-08	3.96E-06
Ethene, trichloro-	kg	0.00E+00	1.01E-12	7.07E-11
Ethylene oxide	kg	0.00E+00	8.38E-10	4.86E-08
Fluoranthene	kg	1.06E-10	1.10E-09	5.85E-08
Fluorene	kg	1.36E-10	1.41E-09	7.5E-08
Fluoride	kg	1.10E-08	1.65E-07	1.76E-05
Formaldehyde	kg	1.08E-04	3.58E-05	0.103048
Formic acid	kg	0.00E+00	0.00E+00	0.0785
Furan	kg	6.91E-13	7.65E-12	4.06E-10
Glyphosate	kg	0.00E+00	7.03E-14	3.85E-08
HAPs	kg	0.00E+00	1.72E-06	0.003754
HAPS, unspecified	kg	0.00E+00	2.96E-07	0
Heat, waste	MJ	0.00E+00	1.19E-03	4.405602
Hexanal	kg	0.00E+00	0.00E+00	0.0159
Hexane	kg	4.72E-12	5.38E-11	2.79E-07
Hydrazine, methyl-	kg	1.20E-11	1.37E-10	3.84E-08
Hydrocarbons, unspecified	kg	2.01E-06	3.05E-05	1.991914
Hydrogen	kg	0.00E+00	4.28E-10	3.05E-07
Hydrogen chloride	kg	1.90E-04	1.97E-03	0.103528
Hydrogen fluoride	kg	2.24E-05	2.32E-04	0.012345
Hydrogen sulfide	kg	3.89E-13	4.18E-12	2.91E-10
Indeno(1,2,3-cd)pyrene	kg	9.10E-12	9.43E-11	5.02E-09
Iron	kg	0.00E+00	4.99E-10	9.64E-10
Isophorone	kg	4.09E-11	4.66E-10	1.31E-07
Isoprene	kg	3.95E-04	4.24E-03	0.295177
Kerosene	kg	1.67E-07	2.53E-06	0.000159
Lead	kg	8.99E-08	9.78E-07	0.000149
Limonene	kg	0.00E+00	0.00E+00	0.000724
Magnesium	kg	1.64E-06	1.70E-05	0.000906
Manganese	kg	1.21E-07	9.23E-06	5.89E-05
Mercaptans, unspecified	kg	1.45E-08	1.74E-07	4.9E-05
Mercury	kg	1.58E-08	1.53E-07	9.3E-06

Substance	Unit	Forestry operations	Wood residue production	Hardboard production
Metals, unspecified	kg	4.47E-14	2.25E-04	2.18E-08
Methane	kg	2.19E-02	2.59E-02	1.550027
Methane, biogenic	kg	0.00E+00	6.11E-06	0.013328
Methane, bromo-, Halon 1001	kg	1.13E-11	1.29E-10	3.62E-08
Methane, chlorodifluoro-, HCFC-22	kg	0.00E+00	6.97E-15	4.04E-13
Methane, chlorotrifluoro-, CFC-13	kg	0.00E+00	6.61E-14	3.84E-12
Methane, dichloro-, HCC-30	kg	1.21E-07	2.05E-06	5.22E-05
Methane, dichlorodifluoro-, CFC-12	kg	5.99E-10	3.00E-10	8.28E-09
Methane, fossil	kg	1.55E-03	1.14E-03	0.112012
Methane, monochloro-, R-40	kg	3.74E-11	4.26E-10	0.000171
Methane, tetrachloro-, CFC-10	kg	5.99E-11	2.37E-07	2.15E-09
Methanol	kg	0.00E+00	3.12E-05	0.313395
Methyl ethyl ketone	kg	2.75E-11	3.13E-10	0.00341
Methyl methacrylate	kg	1.41E-12	1.61E-11	4.52E-09
Metolachlor	kg	0.00E+00	2.58E-13	1.42E-07
Metribuzin	kg	0.00E+00	1.20E-15	6.56E-10
N-Nitrodimethylamine	kg	0.00E+00	2.25E-13	1.58E-11
Naphthalene	kg	2.18E-08	5.63E-07	4.23E-05
Nickel	kg	1.33E-06	1.45E-06	0.000487
Nitrogen oxides	kg	3.05E-01	9.25E-02	3.154067
Nitrogen, total	kg	0.00E+00	1.76E-07	1.46E-07
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1.02E-02	5.43E-03	0.161001
Organic acids	kg	1.28E-09	1.94E-08	1.22E-06
Organic substances, unspecified	kg	9.27E-07	1.07E-05	0.002836
Other Organic	kg	0.00E+00	5.79E-08	0.000126
PAH, polycyclic aromatic hydrocarbons	kg	1.53E-05	9.08E-07	1.24E-05
Paraquat	kg	0.00E+00	5.23E-15	2.87E-09
Parathion, methyl	kg	0.00E+00	3.95E-15	2.17E-09
Particulates	kg	0.00E+00	6.59E-10	4.81E-10
Particulates, < 10 um	kg	0.00E+00	1.33E-04	0.371093
Particulates, < 2.5 um	kg	0.00E+00	2.84E-04	0.085375
Particulates, > 10 um	kg	0.00E+00	6.17E-04	0.002853
Particulates, > 2.5 um, and < 10um	kg	9.39E-03	4.47E-03	0.048911
Particulates, unspecified	kg	1.69E-03	1.42E-01	2.525637
Pendimethalin	kg	0.00E+00	2.69E-14	1.47E-08
Permethrin	kg	0.00E+00	2.41E-15	1.32E-09
Phenanthrene	kg	4.03E-10	4.17E-09	2.22E-07
Phenol	kg	1.13E-12	2.41E-07	0.120301
Phenols, unspecified	kg	6.12E-08	3.46E-07	2.26E-05
Phorate	kg	0.00E+00	1.24E-15	6.79E-10
Phosphate	kg	0.00E+00	4.02E-09	2.93E-09
Phthalate, dioctyl-	kg	5.14E-12	5.86E-11	1.65E-08
Polycyclic organic matter, unspecified	kg	0.00E+00	1.68E-13	9.77E-12
Potassium	kg	0.00E+00	8.85E-08	1.71E-07
Propanal	kg	2.68E-11	2.61E-07	0.053033
Propene	kg	2.35E-04	1.40E-05	0.00019
Propylene oxide	kg	0.00E+00	2.80E-09	1.62E-08
Pyrene	kg	4.92E-11	5.10E-10	2.72E-08
Radioactive species, unspecified	Bq	8.45E+03	8.75E+04	4652962
Radionuclides (Including Radon)	kg	9.33E-06	1.41E-04	0.008875
Selenium	kg	2.07E-07	2.04E-06	0.000112
Simazine	kg	0.00E+00	1.70E-14	9.3E-09
Sodium	kg	0.00E+00	2.04E-09	3.94E-09
Styrene	kg	1.76E-12	2.01E-11	5.65E-09
Sulfur	kg	0.00E+00	7.94E-11	3.9E-05

Substance	Unit	Forestry operations	Wood residue production	Hardboard production
Sulfur dioxide	kg	9.42E-03	5.63E-02	4.039151
Sulfur monoxide	kg	1.69E-02	8.74E-03	0.430812
Sulfur oxides	kg	0.00E+00	1.58E-04	0.036752
Sulfur, total reduced	kg	0.00E+00	6.31E-09	1.22E-08
Sulfuric acid, dimethyl ester	kg	3.38E-12	3.86E-11	1.09E-08
t-Butyl methyl ether	kg	2.47E-12	2.81E-11	7.91E-09
Tar	kg	1.36E-11	1.45E-10	1.01E-08
Terbufos	kg	0.00E+00	4.22E-14	2.32E-08
TOC, Total Organic Carbon	kg	0.00E+00	2.15E-05	1.95E-09
Toluene	kg	3.73E-05	2.23E-06	0.00188
Toluene, 2,4-dinitro-	kg	1.97E-14	2.25E-13	6.33E-11
Trichloroethane	kg	0.00E+00	0.00E+00	3.6E-08
Vinyl acetate	kg	5.36E-13	6.11E-12	1.72E-09
VOC, volatile organic compounds	kg	7.99E-03	4.34E-03	1.998712
Wood (dust)	kg	0.00E+00	4.14E-04	0.336957
Xylene	kg	2.60E-05	1.55E-06	9.77E-05
Zinc	kg	6.33E-10	6.52E-09	2.39E-07

13.4 Water Emissions – Economic Allocation

Table 34 Water emissions released per 1 m3 of hardboard, North American average (economic allocation)

Substance	Unit	Forest operations	Wood residue production	Hardboard production
2-Hexanone	kg	1.26E-07	7.03E-08	3.35E-06
2-Methyl-4-chlorophenoxyacetic acid	kg	0.00E+00	1.89E-17	1.03E-11
2-Propanol	kg	0.00E+00	5.94E-12	5.94E-09
2,4-D	kg	0.00E+00	1.01E-15	5.54E-10
4-Methyl-2-pentanone	kg	8.10E-08	4.52E-08	2.15E-06
Acetaldehyde	kg	0.00E+00	8.82E-10	5.12E-08
Acetochlor	kg	0.00E+00	1.40E-14	7.68E-09
Acetone	kg	1.93E-07	1.08E-07	5.12E-06
Acidity, unspecified	kg	0.00E+00	1.82E-14	1.73E-03
Acids, unspecified	kg	2.53E-10	5.57E-09	3.68E-04
Alachlor	kg	0.00E+00	1.38E-15	7.56E-10
Aluminium	kg	1.67E-03	8.95E-04	3.39E-02
Aluminum	kg	0.00E+00	2.39E-08	4.62E-08
Ammonia	kg	3.61E-04	1.97E-04	8.49E-03
Ammonia, as N	kg	1.27E-10	1.36E-09	9.50E-08
Ammonium, ion	kg	7.45E-08	-1.64E-06	5.41E-04
Antimony	kg	1.04E-06	5.33E-07	1.94E-05
Arsenic	kg	5.28E-06	2.93E-06	1.32E-04
Arsenic, ion	kg	0.00E+00	8.73E-12	1.66E-11
Atrazine	kg	0.00E+00	2.73E-14	1.50E-08
Barium	kg	2.28E-02	1.17E-02	4.33E-01
Bentazone	kg	0.00E+00	1.11E-16	6.11E-11
Benzene	kg	3.23E-05	1.84E-05	8.59E-04
Benzene, 1-methyl-4-(1-methylethyl)-	kg	1.93E-09	1.08E-09	5.12E-08
Benzene, ethyl-	kg	1.82E-06	1.02E-06	4.83E-05
Benzene, pentamethyl-	kg	1.44E-09	8.07E-10	3.84E-08
Benzenes, alkylated, unspecified	kg	9.11E-07	4.68E-07	1.71E-05
Benzo(a)pyrene	kg	0.00E+00	1.40E-09	9.80E-08
Benzoic acid	kg	1.95E-05	1.09E-05	5.20E-04
Beryllium	kg	2.94E-07	1.58E-07	6.81E-06
Biphenyl	kg	5.90E-08	3.03E-08	1.11E-06
BOD5, Biological Oxygen Demand	kg	3.52E-03	1.22E-02	2.10E+00
Boron	kg	6.05E-05	3.38E-05	1.61E-03
Bromide	kg	4.13E-03	2.31E-03	1.10E-01
Bromoxynil	kg	0.00E+00	1.47E-16	8.08E-11
Cadmium	kg	7.80E-07	4.46E-07	2.02E-05
Cadmium, ion	kg	0.00E+00	1.42E-12	2.76E-12
Calcium	kg	6.19E-02	3.46E-02	1.65E+00
Calcium, ion	kg	0.00E+00	1.13E-07	2.22E-07
Carbofuran	kg	0.00E+00	2.09E-16	1.14E-10
CFCs, unspecified	kg	0.00E+00	5.94E-12	5.94E-09
Chloride	kg	6.96E-01	3.89E-01	1.85E+01
Chlorpyrifos	kg	0.00E+00	1.61E-15	8.81E-10
Chromate	kg	0.00E+00	9.32E-13	6.52E-11
Chromium	kg	4.39E-05	2.20E-05	7.29E-04
Chromium III	kg	3.31E-06	2.19E-06	1.45E-04
Chromium VI	kg	1.85E-07	9.26E-08	2.55E-06
Chromium, ion	kg	0.00E+00	1.32E-11	3.02E-11
Cobalt	kg	4.27E-07	2.39E-07	1.14E-05
COD, Chemical Oxygen Demand	kg	6.69E-03	3.68E-03	7.84E+00

Substance	Unit	Forest operations	Wood residue production	Hardboard production
Copper	kg	5.49E-06	3.92E-06	1.84E-04
Copper, ion	kg	0.00E+00	1.36E-11	2.88E-11
Cumene	kg	0.00E+00	4.48E-07	3.27E-07
Cyanazine	kg	0.00E+00	2.41E-16	1.32E-10
Cyanide	kg	1.39E-09	1.61E-07	1.12E-05
Decane	kg	5.62E-07	3.14E-07	1.49E-05
Detergent, oil	kg	1.62E-05	9.22E-06	4.60E-04
Dibenzofuran	kg	3.66E-09	2.05E-09	9.74E-08
Dibenzothiophene	kg	3.15E-09	1.75E-09	8.23E-08
Dicamba	kg	0.00E+00	1.42E-15	7.78E-10
Dimethenamid	kg	0.00E+00	3.35E-15	1.84E-09
Dipropylthiocarbamic acid S-ethyl ester	kg	0.00E+00	1.38E-15	7.59E-10
Disulfoton	kg	0.00E+00	8.26E-17	4.53E-11
Diuron	kg	0.00E+00	2.32E-17	1.27E-11
DOC, Dissolved Organic Carbon	kg	7.77E-13	8.26E-07	6.03E-07
Docosane	kg	2.06E-08	1.15E-08	5.48E-07
Dodecane	kg	1.07E-06	5.95E-07	2.83E-05
Eicosane	kg	2.93E-07	1.64E-07	7.80E-06
Fluorene	kg	0.00E+00	1.65E-14	9.57E-13
Fluorene, 1-methyl-	kg	2.19E-09	1.23E-09	5.83E-08
Fluorenes, alkylated, unspecified	kg	5.28E-08	2.71E-08	9.91E-07
Fluoride	kg	1.21E-06	4.08E-05	1.17E-03
Fluorine	kg	2.61E-08	1.34E-08	5.02E-07
Furan	kg	0.00E+00	2.18E-13	2.18E-10
Glyphosate	kg	0.00E+00	3.01E-15	1.65E-09
Hexadecane	kg	1.16E-06	6.50E-07	3.09E-05
Hexanoic acid	kg	4.05E-06	2.26E-06	1.08E-04
Hydrocarbons, unspecified	kg	9.72E-13	2.28E-10	2.18E-07
Iron	kg	3.32E-03	1.82E-03	7.19E-02
Lead	kg	1.11E-05	6.09E-06	2.57E-04
Lead-210/kg	kg	2.00E-15	1.12E-15	5.32E-14
Lithium	kg	9.93E-04	1.69E-03	2.24E-01
Lithium, ion	kg	0.00E+00	2.35E-08	5.94E-08
m-Xylene	kg	5.84E-07	3.26E-07	1.55E-05
Magnesium	kg	1.21E-02	6.76E-03	3.22E-01
Manganese	kg	2.17E-05	4.12E-05	2.25E-03
Mercury	kg	1.83E-08	1.09E-08	4.32E-07
Metallic ions, unspecified	kg	1.19E-11	5.16E-10	4.68E-08
Methane, monochloro-, R-40	kg	7.76E-10	4.33E-10	2.06E-08
Methyl ethyl ketone	kg	1.55E-09	8.67E-10	4.12E-08
Metolachlor	kg	0.00E+00	1.11E-14	6.07E-09
Metribuzin	kg	0.00E+00	5.13E-17	2.81E-11
Molybdenum	kg	4.43E-07	2.47E-07	1.18E-05
n-Hexacosane	kg	1.29E-08	7.19E-09	3.42E-07
Naphthalene	kg	3.51E-07	1.85E-07	8.58E-06
Naphthalene, 2-methyl-	kg	3.05E-07	1.71E-07	8.12E-06
Naphthalenes, alkylated, unspecified	kg	1.49E-08	7.66E-09	2.80E-07
Nickel	kg	5.21E-06	2.81E-06	1.20E-04
Nickel, ion	kg	0.00E+00	1.30E-16	3.75E-16
Nitrate	kg	8.52E-14	2.76E-10	1.61E-06
Nitrate compounds	kg	3.43E-12	3.68E-11	2.56E-09
Nitric acid	kg	7.69E-09	8.25E-08	5.75E-06
Nitrogen, total	kg	1.85E-07	2.99E-06	2.55E-04
o-Cresol	kg	5.54E-07	3.10E-07	1.47E-05
o-Xylene	kg	0.00E+00	3.51E-14	5.75E-09
Octadecane	kg	2.87E-07	1.61E-07	7.64E-06

Substance	Unit	Forest operations	Wood residue production	Hardboard production
Oils, unspecified	kg	4.45E-04	2.55E-04	1.19E-02
Organic compounds (dissolved)	kg	0.00E+00	0.00E+00	2.22E-04
Organic substances, unspecified	kg	0.00E+00	3.33E-09	2.33E-07
p-Cresol	kg	5.98E-07	3.34E-07	1.59E-05
p-Xylene	kg	0.00E+00	3.51E-14	5.75E-09
Paraquat	kg	0.00E+00	2.24E-16	1.23E-10
Parathion, methyl	kg	0.00E+00	1.69E-16	9.28E-11
Pendimethalin	kg	0.00E+00	1.15E-15	6.31E-10
Permethrin	kg	0.00E+00	1.03E-16	5.67E-11
Phenanthrene	kg	5.35E-09	2.83E-09	1.14E-07
Phenanthrenes, alkylated, unspecified	kg	6.19E-09	3.18E-09	1.16E-07
Phenol	kg	8.18E-06	4.10E-06	1.38E-04
Phenol, 2,4-dimethyl-	kg	5.40E-07	3.02E-07	1.44E-05
Phenols, unspecified	kg	1.55E-06	1.28E-06	1.09E-04
Phorate	kg	0.00E+00	3.20E-17	1.76E-11
Phosphate	kg	0.00E+00	1.68E-05	1.36E-04
Phosphorus	kg	0.00E+00	3.62E-09	3.72E-05
Phosphorus compounds, unspecified	kg	0.00E+00	5.93E-13	3.25E-07
Phosphorus, total	kg	0.00E+00	7.18E-09	7.18E-06
Process solvents, unspecified	kg	0.00E+00	2.18E-11	2.18E-08
Propene	kg	0.00E+00	1.65E-07	1.20E-07
Radioactive species, Nuclides, unspecified	Bq	1.08E+01	1.64E+02	1.03E+04
Radium-226/kg	kg	6.96E-13	3.89E-13	1.85E-11
Radium-228/kg	kg	3.56E-15	1.99E-15	9.48E-14
Selenium	kg	2.28E-07	4.98E-07	2.86E-05
Silver	kg	4.05E-05	2.26E-05	1.07E-03
Simazine	kg	0.00E+00	7.27E-16	3.99E-10
Sodium	kg	1.96E-01	1.10E-01	5.22E+00
Sodium, ion	kg	0.00E+00	3.58E-07	7.05E-07
Solids, inorganic	kg	1.96E-11	2.10E-10	1.46E-08
Solved solids	kg	0.00E+00	1.61E-06	3.19E-06
Solved substances, inorganic	kg	0.00E+00	0.00E+00	2.95E-04
Strontium	kg	1.05E-03	5.87E-04	2.79E-02
Styrene	kg	0.00E+00	4.01E-14	2.79E-11
Sulfate	kg	1.55E-03	3.07E-03	1.81E-01
Sulfide	kg	9.49E-07	9.69E-07	2.09E-04
Sulfur	kg	5.10E-05	2.85E-05	1.36E-03
Sulfuric acid	kg	0.00E+00	7.25E-10	5.07E-08
Surfactants	kg	0.00E+00	1.62E-12	2.92E-07
Suspended solids, unspecified	kg	9.09E-01	5.06E-01	2.76E+01
Tar	kg	1.94E-13	2.08E-12	1.45E-10
Terbufos	kg	0.00E+00	1.09E-15	5.99E-10
Tetradecane	kg	4.67E-07	2.61E-07	1.24E-05
Thallium	kg	2.19E-07	1.12E-07	4.09E-06
Tin	kg	4.23E-06	2.24E-06	9.14E-05
Titanium	kg	1.60E-05	8.19E-06	2.98E-04
Titanium, ion	kg	0.00E+00	1.52E-11	2.15E-11
TOC, Total Organic Carbon	kg	0.00E+00	8.26E-07	8.78E-07
Toluene	kg	3.05E-05	1.71E-05	8.12E-04
Vanadium	kg	5.23E-07	2.92E-07	1.39E-05
Waste water/m3	m3	0.00E+00	6.40E-03	2.88E-03
Water	kg	0.00E+00	2.38E+00	0.00E+00
Xylene	kg	1.64E-05	9.13E-06	4.30E-04
Yttrium	kg	1.30E-07	7.25E-08	3.45E-06
Zinc	kg	3.85E-05	2.15E-05	8.44E-04
Zinc, ion	kg	0.00E+00	3.10E-10	7.42E-10

14 Appendix C – Substance contribution analysis

Table 35 Substance contribution analysis to Global Warming Potential (GWP) (kg CO_2 eq.) by life cycle stage total percent basis and values are displayed per 1.0 m^3.

		Mass Allocation				Economic Allocation			
GWP substances	**Compartment type**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Total of all compartments		**100.00%**	17.43	29.43	611.62	**100.00%**	17.43	16.98	708.84
Carbon dioxide, fossil (CO_2)	Air	**93.75%**	16.84	28.09	572.43	**93.71%**	16.84	16.25	663.42
Methane (CH_4)	Air	**5.77%**	0.59	1.27	36.11	**5.80%**	0.59	0.68	41.85
Dinitrogen monoxide (N_2O)	Air	**0.48%**	0.00	0.07	3.08	**0.49%**	0.00	0.06	3.57
Remaining substances	Air	**0.00%**	0.00	0.00	0.00	**0.00%**	0.00	0.00	0.00

Table 36 Substance contribution analysis to Acidification (kg SO_2 eq.) by life cycle stage total percent basis and values are displayed per 1.0 m^3.

		Mass Allocation				Economic Allocation			
GWP substances	**Compartment type**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Total of all compartments		**100.00%**	0.2403	0.2461	5.8563	**100.00%**	0.2401	0.1322	6.8461
Sulfur dioxide	Air	**59.04%**	0.0094	0.1256	3.4575	**56.87%**	0.0094	0.0563	4.0392
Nitrogen oxides	Air	**32.41%**	0.2136	0.1039	1.8977	**34.44%**	0.2136	0.0647	2.2078
Sulfur monoxide	Air	**6.32%**	0.0169	0.0112	0.3702	**6.32%**	0.0169	0.0087	0.4308
Remaining substances	Air	**2.23%**	0.0004	0.0054	0.1308	**2.37%**	0.0002	0.0024	0.1682

Table 37 . Substance contribution analysis to Eutrophication (kg N eq.) by life cycle stage total percent basis and values are displayed.

		Mass Allocation				Economic Allocation			
GWP substances	**Compartment type**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**	**TOTAL**	**Forestry Operations**	**Wood residue production**	**Hardboard production**
Total of all compartments		**100.00%**	0.0143	0.0086	0.5574	**100.00%**	0.0143	0.0051	0.6459
COD, Chemical Oxygen Demand	Water	**58.43%**	0.0003	0.0003	0.3385	**59.03%**	0.0003	0.0002	0.3922
Nitrogen oxides	Air	**24.24%**	0.0135	0.0066	0.1205	**23.64%**	0.0135	0.0041	0.1397
BOD5, Biological Oxygen Demand	Water	**15.90%**	0.0002	0.0015	0.0906	**15.90%**	0.0002	0.0006	0.1050
Ammonia	Air	**1.07%**	0.0003	0.0002	0.0057	**1.06%**	0.0003	0.0002	0.0066
Ammonia	Water	**0.20%**	0.0000	0.0000	0.0011	**0.20%**	0.0000	0.0000	0.0013
Remaining substances	Air/water	**0.17%**	0.0000	0.0001	0.0009	**0.16%**	0.0000	0.0000	0.0010

15 Conversion factors

Table 38 Common conversions from English units to SI

To convert from	To	Multiply by
Cubic feet (ft^3)	Cubic meter (m^3)	0.02831685
Pounds (avdp) (lb)	Kilograms (kg)	0.4535924
Cubic inches (in^3)	cubic centimeters (cm^3)	16.393
Btu's	Joules	1054
Cubic yards (yd^3)	m^3	0.7645549
Feet	meters	0.305
Gallons (U. S.)	Liters	3.785
Kilowatt - hours (kWh)	Mega joules	3.6
Miles	kilometers	1.609
Ounces (avdp)	kilograms	0.028
Square feet	square meters	0.093
Tons (short)	kilograms	907.185
Tons (short)	metric ton	0.9071847
Pounds	metric ton	0.0004
Watts	joules / sec	1
Yards	meters	0.914
Acres	hectares	0.405

Sources: Starr (1971).

Table 39 Electricity grids and dataset name by region and source

Region	North American grid	Source
US Average	Electricity, at grid, US, 2008	NREL (2012)
Canadian – Nova Scotia	Electricity, high voltage {CA-NS}| market for | Alloc Def, U	Ecoinvent LCI Database
Pacific Northwest	Electricity, at grid, NWPP, 2010	USEPA (2014): p. 6
Northeastern/North central (Midwest)	Electricity, at grid, MRO, 2010	USEPA (2014): p. 9
Virginia/Carolina	Electricity, at eGrid, SRVC, 2010	USEPA (2014): p. 6

Table 40 Energy contents and densities of various fuels

Fuel	HHV[1, 2, 3, 4] MJ/kg	Density	Density Units
Coal	26.19		
Distillate fuel oil[5]	45.54	0.85	kg/L
Liquid propane gas	54.05	0.49	kg/L
Natural gas	54.45	0.70	kg/m^3
Residual fuel oil	43.45	0.96	kg/L
Wood	20.93		
Uranium	381,000.00		
Gasoline	48.36	0.72	kg/L
Diesel	44.00	0.88	kg/L
Kerosene			

[1] Hodgman (1955).
[2] Channiwala and Parikh (2002).
[3] Todreas and Kazimi (1993).
[4] Used in the present study.
[5] Same as for crude oil.