Life-Cycle Assessment for Wood-Fired Boilers Used in the Wood Products Industry*

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Abstract

Many wood production facilities use wood-based fuels for steam generation for drying wood or pressing boards or panels. This process contributes to the life-cycle impacts of the products produced downstream. Past life-cycle assessment studies of wood products have relied on wood boiler data sets that represent both the paper and the wood products industries as well as on secondary data from the US Environmental Protection Agency primarily based on the potential to emit or collect from an uncontrolled source. Primary data were collected by survey for the material and energy inputs and outputs of wood-fired boilers at lumber and plywood wood production facilities in the Pacific Northwest and Southeast regions of the United States. The results were averaged to create a life-cycle inventory model to represent wood-fired boilers at wood production facilities. Results indicated that regional differences, as well as type of wood waste burned, did not warrant separate boiler data sets for each industry and region. The model is useful for including the effects of steam production in the life-cycle assessment of wood products. The primary data used in the model should better represent wood-fired boilers used in US wood production facilities than existing data sets do.

Most wood products production facilities generate residues, such as bark, chips, sawdust, hog fuel, trimmings, shavings, mill rejects, and sander dust. These can be green (typically around 50% moisture content [MC], wet basis) or dry, depending on the stage of production. Residues with a higher commercial value are sold as chips for pulp, bark for landscaping, or sawdust for animal bedding or in a variety of forms to wood composite producers for products such as particleboard and fiberboard; however, wood residue is also used extensively in wood production processes as energy to produce steam or to directly heat processes, such as dryers. Steam is used to heat presses for panel products, heating and humidification of dryers, power turbines in some cases, and other operations (Milota 2015a, 2015b; Puettmann et al. 2016a, 2016b).

Within the solid lumber industry, approximately 44 billion kg (bone-dry mass) of mill residues are produced annually, 23 percent (10 billion kg) of which is combusted on-site (Bergman and Bowe 2008, 2010; Milota 2015a, 2015b). The largest percentage (36%) of use occurs at hardwood lumber facilities in the Northeast/North Central regions of the United States (Bergman and Bowe 2008). In 2012, US softwood lumber producers in the Pacific Northwest (PNW) and the Southeast (SE) used 2.4 and 2.1 billion kg of residues for energy, representing 24 and 20 percent of their total mill residues, respectively (Milota 2015a, 2015b). The US softwood plywood industry, located mainly in the PNW and SE, generates 3.2 billion kg of residues annually, based on 2012 data (Kaestner 2015); of that quantity, 35 percent (1.1 billion kg) was used to produce thermal energy for log conditioning, veneer drying, and panel pressing (Puettmann et al. 2016a, 2016c).

Over the past 20 years, primary data on primary wood product production and associated coproducts have been

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collected and used in documenting the environmental impact of these products. Coproducts can represent a significant portion (by mass) of the overall wood output. Table 1 shows the type of wood residues produced and their allocated use as a fuel source on-site. Producers of primary wood products, such as lumber and plywood, utilize coproducts for fuel more commonly than do manufacturers of secondary wood products, such as glued-laminated timber (glulam), laminated veneer lumber (LVL), and particleboard (Table 1).

Fuel Switching Impacts

Economics can have a significant impact on the use of these coproducts. For example, wood heating is less common in the production of secondary products, such as LVL and glulam (Bergman and Alanya-Rosenbaum 2016a, 2016b, 2016c, 2016d; Bowers et al. 2016a, 2016b), because secondary wood products facilities cannot generate enough wood waste to justify the expense of a wood-fired wood boiler. Therefore, these facilities are more likely to use natural gas and electricity for any drying or pressing that may be required (Table 2).

The environmental effects of wood combustion versus natural gas on carbon emissions are significant in life-cycle assessment (LCA). Global warming potential (GWP; fossil carbon, kilograms of CO_2 equivalent) is significantly lower when wood fuel is used instead of natural gas (Puettmann and Lippke 2010). Past work investigating fuel substitutions in lumber mills showed that the carbon impacts of fuel substitution are significant. One scenario using a base case in which 46 percent wood waste and 54 percent natural gas as boiler inputs were substituted for 100 percent natural gas resulted in a 58 percent increase in GWP (Puettmann and Lippke 2010). Further substitution scenarios showed that a combination of mill residues and wood pellets decreased GWP by 33 percent from the base scenario (46:54, wood:natural gas). The greatest reduction was 47 percent, which resulted from replacing natural gas (54%) with forest residuals.

Data sources for LCA

The Consortium for Research on Renewable Industrial Materials (CORRIM) has derived life-cycle inventory (LCI) data for 12 major wood products produced in four regions of

Table 1.—Sources of woody fuels inputs to boilers based on previous Consortium for Research on Renewable Industrial Materials studies.[a]

Wood product	Fuel	% of total residues used as fuel	Reference
Cellulosic fiberboard	Wood fuel	96	Bergman (2015b)
	Wood fuel	4	
Glulam	Sawdust	97	Bowers et al. (2016a, 2016b)
	Shavings		
	Trimmings		
	Wood fuel	3	
Hardboard/engineered wood siding and trim	Culled board	23	Bergman (2015a)
	Baghouse Dust	17	
	Sander dust	9	
	Sawdust	3	
	Wood fuel	48	
Laminated strand lumber	Wood fuel	100	Puettmann and Oneil (2015)
Lumber, hardwood	Sawmill residue	66	Bergman and Bowe (2008)
	Planer residue	20	
	Wood fuel	14	
Lumber, softwood	Sawmill sawdust	26	Milota (2015a, 2015b)
	Sawmill hog fuel	45	
	Sawmill chips	2	
	Planer shavings	14	
	Hog fuel	13	
Medium-density fiberboard	Sander dust	20	Wilson (2010a)
	Wood fuel	15	
	Wood fuel	65	
Oriented strand board	Hog fuel	92	Kaestner (2015), Puettmann et al. (2016a)
	Hog fuel	8	
Particleboard	Sander dust	93	Wilson (2010b)
	Wood fuel	7	
Plywood, softwood	Bark from debarker	51	Kaestner (2015), Puettmann et al. (2016a, 2016b)
	Debarker wood waste	5	
	Veneer clippings	7	
	Veneer downfall	1	
	Lap-up scrap from press	1	
	Panel trim	18	
	Sawdust	1	
	Wood fuel	17	

[a] Italics indicate that the fuel was purchased from off-site.

Table 2.—Allocation of primary fuels used in the production of selected wood products industries.[a]

Product/region[b]	Nonrenewable (%)		Renewable (%)		Reference
	Fossil	Nuclear	Biomass	Other	
Glulam/PNW	55	6	39	0	Bowers et al. (2016a)
Glulam/SE	56	13	31	0	Bowers et al. (2016b)
LVL/PNW	90	5	1	3	Bergman and Alanya-Rosenbaum (2016a)
LVL/SE	88	11	1	0	Bergman and Alanya-Rosenbaum (2016b)
LSL/US	33	10	57	1	Puettmann and Oneil (2015)
I-joist/PNW	91	4	2	3	Bergman and Alanya-Rosenbaum (2016c)
I-joist/SE	90	8	2	0	Bergman and Alanya-Rosenbaum (2016d)
Cellulosic fiberboard	71	7	17	5	Bergman (2015b)
Hardboard	35	7	58	1	Bergman (2015a)
OSB	73	10	16	1	Puettmann et al. (2016c)

[a] Rows do not equal 100 owing to rounding.
[b] PNW = Pacific Northwest; SE = Southeast; LVL = laminated veneer lumber; US = United States; OSB = oriented strandboard.

the United States. The LCI data cover forest regeneration to the final product at the mill gate, including structural and nonstructural products. For the past 20 years, CORRIM has relied on publicly available secondary data for environmental impacts related to wood combustion in boilers (US Environmental Protection Agency [EPA] 2003, Franklin Associates 2004, US Life Cycle Inventory [USLCI] 2008). The latest database is available through the USLCI (2008) (https://uslci.lcacommons.gov/uslci/search), and it is based on both Franklin Associates (2004) and EPA (2003) combined emission factors collected from the paper and wood production industries. In addition, emission factors are reported as the ''potential to emit'' and do not consider reductions due to the emission control devices that are in common use on boilers today, such as baghouses and electrostatic precipitators (Milota 2015a, 2015b; Bergman and Alanya-Rosenbaum 2016b; Puettmann et al. 2016a, 2016b, 2016c) (Table 3).

Goal of the Study

Primary data on the material and fuel inputs and energy and emission outputs associated with the combustion of mill residues in wood boilers are needed in order to accurately assess their impacts. To enhance the quality of CORRIM's wood production data, selected wood products manufacturers were surveyed to collect primary wood boiler data from softwood lumber and plywood facilities operating in the PNW and SE regions of the United States. The goal of the study was to create an LCI process that can represent the impacts of using wood-fired boilers to burn wood residues in the LCA of wood products (excluding pulp and paper) in the United States. The current work includes only wood-fired boilers producing steam, not direct-fired equipment.

Methods

Data were collected by survey from 14 wood production facilities in the PNW and SE regions for the calendar year 2012. The boiler data were collected within a more comprehensive survey designed to survey the entire wood production process; however, boiler data were collected separately in cases where the general production surveys produced limited or inconsistent data. The mills included four facilities producing plywood and 10 producing lumber, and they represented the range of mill sizes. Half of the facilities were in the PNW region and the other half in the SE region.

Survey

The surveys were done by mail or e-mail, and follow-up questions were conducted by phone. The follow-up occurred if a value was an outlier compared with other mills or a response (such as water use) was blank when it should not have been.

Survey respondents were asked to provide information on the type of boiler used in the facility as well as when updates were made and the type of pollution control equipment used.

The boiler survey requested information for all material and energy inputs and outputs that occurred owing to the on-site energy generation. The material inputs included the quantities of lubricants and oils for stationary equipment; lubricants, oils, and antifreeze for rolling stock; solvents; water; and water treatment chemicals. The energy inputs

Table 3.—Types of emission control device (ECD), as reported in primary surveys from selected industries, and where they are used.[a]

Product	ECD	Process	Reference
LVL/SE	Baghouse, RCO, RTO	Boilers, presses	Bergman and Alanya-Rosenbaum (2016b)
Lumber	Baghouse, ESP	Boilers, planning	Milota (2015a, 2015b)
Plywood	RTO, ESP	Boilers, pressing, trimming	Puettmann et al. (2016a, 2016b)
OSB	RTO, ESP		Puettmann et al. (2016c)
Hardboard	Baghouses, RTO, wet scrubbers, biofiltration systems	Boilers, hot presses, dryers refiners, tempering ovens, humidification kilns, sanding/finishing	Bergman (2015a)

[a] LVL = laminated veneer lumber; SE = Southeast; RCO = regenerative catalytic oxidizer; RTO = regenerative thermal oxidizer; ESP = electrostatic precipitator; OSB = oriented strandboard.

included the types and quantities of fuel burned and all transportation distances from off-site sources; the quantities of natural gas, propane, or oil that might be used for start-up; quantities and types of fuels for the machinery to handle wood fuel; and electricity. The outputs included the amount of steam produced and its pressure, air emissions, liquid emissions, and solid emissions. Some lines in the survey listed specific items that the authors expected mills to report because without these items it would be impossible to operate a boiler. There were also blank lines for input for less common items, such as urea added to the boiler exhaust.

Functional unit

A functional unit expresses the function of studied product in quantitative terms and serves as the basis for all calculations. It also serves as a unit of comparison in comparative studies. The functional unit for this study was the process of combusting 1 kg of wood residue in a boiler. The 1 $kg_{residue}$ was expressed as bone dry. All input and output data were allocated to the functional unit in accordance with the International Organization for Standardization (2006). A wood input functional unit was used instead of an energy output (steam produced) so that a ''generic'' boiler could be used over all wood boiler types and efficiencies for any wood production facility. The emission factors were based on the combustion of ovendry wood, similar to the design of previous LCI processes for wood combustion boilers (EPA 2003, Franklin Associates 2004, USLCI 2008).

System boundary

The gate-to-gate system boundary for the CORRIM wood boiler (Fig. 1) encompassed the boiler and associated equipment, such as the deaeration tank, economizer, superheater, water treatment, and emissions control, but did not include the distribution system for the steam or the condensate return system. The wood residue included hog fuel, bark, or other wood residue (Table 1) and was expressed on an ovendry basis. Most fuels come from other processes in the mill that are closely monitored, so the fuel inputs were known with high accuracy. Transportation was an input if fuels were produced off-site and was a function of the fuel's green mass and transport distance expressed in tonne-kilometer (t·km). Distances were accurately known, and the quantity of purchased fuel was known with high accuracy from measurements at the facility gate. Other possible fuels included small amounts of natural gas or propane for start-up and fuels for rolling stock. The input materials included all other nonfuel inputs. These were known with high accuracy from purchasing invoices. Ash was an output if destined for agricultural use or an emission if sent to a landfill. The quantities of ash were known with high accuracy from truck weights leaving the facility.

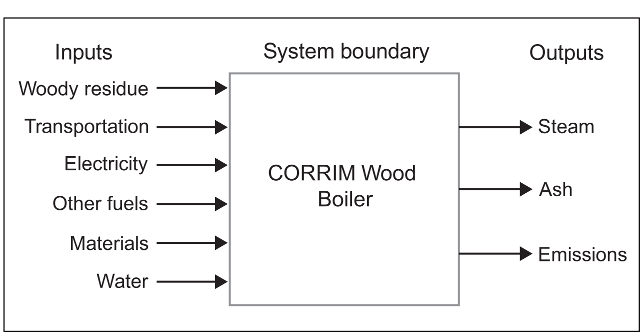

Figure 1.—System boundary for the Consortium for Research on Renewable Industrial Materials (CORRIM) wood boiler process.

Steam production reported at the boiler was confirmed either by what was reported in other surveys for use at the dryers or presses or by an energy balance based on the amount of water evaporated in other processes. This gave a high level of confidence in the values for steam output. Another check was the wood required to produce a unit of steam. This averaged 0.2 $kg_{residue}/kg_{steam}$ and ranged from 0.12 to 0.33 $kg_{residue}/kg_{steam}$. This may seem like a wide variation, but values for three of the four plywood mills were very close to each other (0.13, 0.13, and 0.12 $kg_{residue}/kg_{steam}$), while those for the lumber mills ranged from 0.19 to 0.33 $kg_{residue}/kg_{steam}$. Part of this variability can be attributed to fuel MC. The fuel at plywood mills is drier than that at lumber mills, and the fuel MC at lumber mills can vary widely, depending on species and type of residue.

The CORRIM wood boiler is designed as a gate-to-gate LCI process and can be used as an input in other LCI unit processes that might require a wood boiler. The data were modeled in SimaPro (8+) LCA software for use with other wood production LCI processes (Pré Consultants 2016). If wood fuel inputs are derived from another LCI process and carry the upstream impacts of the forest, log yard, and breakdown, then a cradle-to-gate analysis can be performed.

Calculations rules

Mills reported most values in English units (e.g., cubic feet, pounds, gallons), and standard conversions were made to SI units (e.g., cubic meters, kilograms, liters). Each reported value was converted to a production-based value, for example, from kilograms per year to $kg/kg_{residue}$, where 1 $kg_{residue}$ is the functional unit. The production-based values for each mill were then combined into a weighted average for each input and output. Weighting was based on the mills' 2012 steam production so that the values from mills with greater production received greater weight. These values became the inputs and outputs for the CORRIM wood boiler. If a value was not reported in a survey, plant personnel were contacted to determine whether it was unknown or zero. Zero values were averaged with the other data. Missing or unknown data were not included in the average, which was then based on the steam production of the reporting mills. These input and output values represented an average per kilogram of wood combusted. Only averaged values were reported in order to maintain the confidentiality of the survey participants.

Residues were reported as either green tons or bone dry tons. For the former, an MC was asked in the survey, and the mass was adjusted to an ovendry basis. If an MC was not provided, 50 percent wet basis MC was used for green residues and 15 percent dry basis MC for dry residues (e.g., dry planer shavings). No conversions of wood volume to mass were required.

Results and Discussion

The reporting mills were of average technology. The boiler ages ranged from 4 to 32 years, with most boilers at the newer end of this range. Most sites reported updates to the boiler within the past 5 years, although two had not been

Table 4.—Weighted average production inputs and outputs for the Consortium for Research on Renewable Industrial Materials (CORRIM) wood boiler life-cycle inventory process.[a]

	Value	Unit/m^3
Inputs		
Wood residue 1	Must sum to 1.00	kg
Wood residue 2		
Wood residue 3		
Wood residue 4		
Transport, combination truck, diesel powered/US		t·km
Diesel, combusted in industrial equipment/US	8.05E−04	liters
Gasoline, combusted in equipment/US	3.96E−05	liters
Liquefied petroleum gas, combusted in industrial boiler/US	1.21E−05	liters
Lubricants	1.91E−05	liters
Engine oil	2.22E−05	liters
Hydraulic oil	0.00E+00	liters
Antifreeze	4.81E−07	liters
Ethylene glycol, at plant	1.07E−06	kg
Solvents[b]	7.17E−07	kg
Water treatment	1.23E−04	kg
Boiler streamline treatment	3.67E−06	kg
Urea, as nitrogen, at regional storehouse	3.15E−03	kg
Disposal, ash, to unspecified landfill/kg	7.59E−03	kg
Disposal, solid waste, unspecified, to unspecified landfill/kg	7.26E−06	kg
Disposal, metal, to recycling/kg	3.96E−08	kg
Electricity	8.20E−02	kWh
Natural gas, combusted in industrial boiler/US	1.38E−03	m^3
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 coproducts		
CORRIM wood combusted, at boiler, at mill, kg	1.00E+00	kg
CORRIM wood ash, at boiler, at mill, kg	2.00E−02	kg
Air emissions		
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
Hazardous air pollutants	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 μm	4.71E−04	kg
Particulates, <2.5 μm	1.39E−04	kg
Phenol	6.21E−07	kg
Propanal	5.14E−08	kg
Sulfur dioxide	7.71E−05	kg
Volatile organic compounds	8.76E−04	kg
Dinitrogen monoxide	2.93E−06	kg
Naphthalene	5.77E−08	kg
Other organic	2.11E−07	kg
Emissions to water		
Suspended solids: unspecified	8.35E−07	kg
BOD5 (biological oxygen demand)	2.10E−06	kg

[a] Data are based on 2012 survey data from softwood lumber, plywood, and oriented strandboard industries.
[b] Solvents may contain substances listed on the US Environmental Agency Toxics Release Inventory (www.epa.gov/toxics-release-inventory-tri-program/tri-listed-chemicals [accessed January 2016]).

updated for 20 to 25 years. All boilers had emissions control devices, but these varied from a wet scrubber with or without a multiclone to an electrostatic precipitator or a dry electrostatic precipitator with or without a multi-cyclone.

The LCI process for the CORRIM wood boiler (Table 4) consists of the weighted averages calculated from the surveys and represents wood boilers at production facilities in each region and process. The first four lines are to separate woody fuels by type because each type would carry different upstream impacts into the boiler process. The sum of the four lines must be 1 $kg_{residue}$. The transportation effort for fuels from off-site is entered in line 5. The types of fuel can vary among wood products facilities; the fuel mix in the surveyed mills is shown in Table 5. Most was reported as hog fuel (57%), which can vary considerably in bark content and type of wood. It is generally a green fuel and is often from sawn material too small to make lumber; however, hog fuel can mean any residue that has passed through a hog. A small amount of forest biomass was reported by one facility; it is possible that the use of this type of fuel will increase as carbon impacts related to fossil-based fuels become increasingly important. Of the wood residue boiler inputs reported, 91 percent was generated on-site, and 9 percent was transported from an off-site location.

The higher heating value (HHV) for bone dry wood fuel is 20.92 MJ/kg_{wood}. Evaporating the water in the fuel (1 kg_{water}/kg_{fuel} at 100% dry basis MC) requires approximately 2.4 MJ/kg_{wood}, so 18.5 $MJ/kg_{residue}$ is produced. The CORRIM boiler produces 5.1 kg of steam from 1 $kg_{residue}$ (2 kg at 50% MC). The energy in steam is 2.2 MJ/kg_{steam}, so the energy embodied in the steam is 11.2 MJ. Thus, the boiler thermal efficiency is approximately 61 percent based on the HHV for the fuel. The efficiency is approximately 76 percent based on a lower heating value for bone dry wood of 17 MJ/kg_{wood}.

The other input values in Table 4 include the fuels, lubricants, and antifreeze for stationary equipment and rolling stock. Water is added to make up for water lost from the system either owing to steam spray or from vented condensate receivers. Treatment chemicals are added to the water or steam to prevent corrosion in the piping and vessels. Some of the ash goes to a landfill and is shown as landfill input, while some leaves the facility intended for agricultural use and is shown as a coproduct. In the LCI model, the landfill operation is considered a process (like gasoline use would be) and contains inputs and outputs associated with landfill operations. The survey respondents indicated that the ash is transported 69 km, on average, to fertilizer production facilities. Electricity is used to run various motors and instruments.

Table 5.—Fuel types used at surveyed boilers.

Fuel type	% contribution[a]
Hog fuel	56.8
Sawdust, green	13.2
Shavings	10.7
Hog fuel, purchased	9.1
Other wood	6.1
Bark	3.3
Sawdust, dry	0.37
Wood chips (green)	0.31
Forest biomass	0.12

[a] Values are a percentage of the weighted average.

Table 6.—Consortium for Research on Renewable Industrial Materials wood boiler air emission factors reported in mill survey data collected in 2012.[a]

Air emission	Emission/wood combusted (kg/kg)						
	Weighted avg.	Low	High	SD	Weighted SD	CV	No. of facilities reporting
CO, biogenic	3.23E−03	0.00E+00	3.71E−02	1.16E−02	7.86E−03	2.44E+02	10
CO_2, biogenic	5.60E−01	8.10E−04	9.07E−01	6.58E−01	6.23E−01	1.11E+02	2
Dust	5.62E−04	0.00E+00	4.97E−03	1.59E−03	1.37E−03	2.44E+02	10
HAP, acetaldehyde	1.05E−06	0.00E+00	1.01E−05	3.51E−06	2.04E−06	1.94E+02	8
HAP, acrolein	8.07E−07	0.00E+00	7.12E−06	2.71E−06	1.64E−06	2.03E+02	7
HAP, benzene	1.69E−07	0.00E+00	1.60E−06	4.43E−07	4.96E−07	2.94E+02	13
HAP, formaldehyde	1.26E−05	0.00E+00	2.14E−04	7.18E−05	4.14E−05	3.28E+02	9
HAP, hydrogen chloride	1.17E−06	0.00E+00	1.02E−05	2.95E−06	3.29E−06	2.82E+02	12
HAP, lead	1.75E−07	0.00E+00	1.48E−06	4.18E−07	4.64E−07	2.66E+02	13
HAP, mercury	1.83E−09	0.00E+00	1.36E−08	4.40E−09	3.98E−09	2.17E+02	13
HAP, methanol	7.95E−06	0.00E+00	9.45E−05	3.16E−05	2.53E−05	3.18E+02	9
HAP, phenol	6.21E−07	0.00E+00	4.10E−06	1.29E−06	1.02E−06	1.65E+02	11
HAP, propionaldehyde	5.14E−08	0.00E+00	3.97E−07	1.64E−07	1.17E−07	2.27E+02	7
HAP, total	8.69E−05	0.00E+00	5.35E−04	2.33E−04	1.86E−04	2.14E+02	7
HAP, unspecified	6.27E−06	0.00E+00	1.44E−04	4.82E−05	3.10E−05	1.51E+03	10
NO_x	1.10E−03	0.00E+00	2.83E−03	9.45E−04	7.94E−04	7.25E+01	11
Other, N_2O	2.93E−06	0.00E+00	4.06E−05	1.23E−05	1.10E−05	3.76E+02	11
Other, organic	2.11E−07	0.00E+00	1.88E−06	5.69E−07	6.23E−07	2.95E+02	11
Other	5.77E−08	0.00E+00	5.07E−07	1.46E−07	1.63E−07	2.82E+02	12
Other, methane	2.23E−05	0.00E+00	3.09E−04	9.34E−05	8.38E−05	3.76E+02	11
Particulate, PM_{10}	4.71E−04	0.00E+00	1.86E−03	6.26E−04	5.84E−04	1.24E+02	11
Particulate, $PM_{2.5}$	1.39E−04	0.00E+00	1.10E−03	4.05E−04	3.22E−04	2.32E+02	9
SO_2	7.71E−05	0.00E+00	3.25E−04	1.28E−04	1.01E−04	1.30E+02	8
VOC	8.75E−04	0.00E+00	4.59E−03	1.45E−03	1.59E−03	1.81E+02	11

[a] CV = coefficient of variation; CO = carbon monoxide; CO_2 = carbon dioxide; HAP = hazardous air pollutant; NO_x = nitrogen oxide; N_2O = nitrous oxide; SO_2 = sulfur dioxide; VOC = volatile organic compound.

Table 7.—Emission factor differences as collected in the Consortium for Research on Renewable Industrial Materials (CORRIM) wood boiler survey and the US Life Cycle Inventory database (USLCI 2008).[a]

Substance	Values ($kg_{emission}/kg_{residue}$)		% change in emission factor when using CORRIM 2012 data
	CORRIM wood boiler, 2012	USLCI (2008)	
Air emission			
Acetaldehyde	1.05E−06	7.47E−06	−86
Acrolein	8.07E−07	3.60E−05	−98
Antimony	NR	7.11E−08	—
Arsenic	NR	1.98E−07	—
Benzene	1.69E−07	3.78E−05	−100
Beryllium	NR	9.90E−09	—
Cadmium	NR	3.69E−08	—
Chlorine	NR	7.11E−06	—
Chromium	NR	1.89E−07	—
CO, biogenic	3.23E−03	5.40E−03	−40
CO_2, biogenic[b]	1.76E+00	1.76E+00	0
Cobalt	NR	5.85E−08	—
Dioxin, 2,3,7,8 tetrachlorodibenzo-*p*-	NR	7.74E−14	—
Dust	5.62E−04	NR	—
Formaldehyde	1.26E−05	3.96E-05	−68
HAP, unspecified	6.60E−14	NR	—
HAP, unspecified	1.57E−06	NR	—
HAP, unspecified	4.70E−06	NR	—
HAP, total	8.69E−05	NR	—
Hydrogen chloride	1.17E−06	1.71E−04	−99
Lead	1.75E−07	4.32E−07	−60
Manganese	NR	1.44E−05	—
Mercury	1.83E-09	3.15E−08	−94
Metals, unspecified	NR	3.85E−04	—
Methane, biogenic	2.23E−05	1.89E−04	−88
Methane, dichloro-, HCC-30	NR	2.61E−06	—
Methanol	7.95E−06	NR	—
Naphthalene	NR	8.73E−07	—
Nickel	NR	2.97E−07	—
NO_x	1.10E−03	2.10E−03	−48
Other, N_2O	2.93E−06	NR	—
Other, organic	2.11E−07	NR	—
Other	5.77E−08	NR	—
Particulate, PM_{10}	4.71E−04	4.50E−03	−90
Particulate, $PM_{2.5}$	1.39E−04	3.87E−03	−96
Phenol	6.21E−07	4.59E−07	35
Propionaldehyde	5.14E−08	NR	—
Selenium	NR	2.52E−08	—
SO_2	7.71E−05	2.25E−04	−66
TOC	NR	3.68E−05	—
VOC	8.75E−04	NR	—
Emissions to water			
Suspended solids	9.19E−07	NR	—
BOD	2.31E−06	NR	—
Solid waste			
Ash	7.59E−03	NR	—
Other, inorganics	8.28E−06	NR	—

[a] NR = not reported; CO = carbon monoxide; CO_2 = carbon dioxide; HAP = hazardous air pollutant; NO_x = nitrogen oxide; N_2O = nitrous oxide; SO_2 = sulfur dioxide; TOC = total organic carbon; VOC = volatile organic compounds; BOD = biological oxygen demand.
[b] Did not use survey data. The value used is based on published data for carbon dioxide releases for the combustion of wood.

Boiler air emissions can vary widely from mill to mill, partly because mills typically report their operating permits, which vary by state and even by region within a state (Table 6). The coefficient of variation for the reported values was typically around 200 percent, with some mills reporting zero for some values. Carbon dioxide, nitrogen oxide, and volatile organic compounds are the most abundant emissions, followed by particulates. Methanol and formaldehyde are the hazardous air pollutants (HAPs) emitted in the greatest quantities, 7.95E–6 and 1.25E–5 $kg/kg_{residue}$, respectively. This is on the same order of magnitude as the emissions from drying per kilogram of wood (Milota 2015a, 2015b). An exact comparison is difficult because drying temperature varies among processes and products. The other HAPs in the plywood composite wood products and Maximum Achievable Controlled Technology standards that would be of concern at the dryers and presses include acetaldehyde, acrolein, phenol, and propanal.

Twenty-two emissions were reported in the surveys (Table 7). Thirteen emission types overlapped with previously published data sets. Of these 13 emissions, 12 emissions were reduced by 40 to 99 percent over previously published data sets. One emission, phenol, was higher by 35 percent. Nine emissions reported in the 2012 survey were not reported in previous data sets, while 17 emissions previously reported were not reported in the 2012 surveys.

Air emissions reported in the survey varied from the EPA (2003) values and USLCI (2008), partly because the emissions were reported after a control device had been installed. Most HAPs were 68 to 99 percent less than the values in the previous data sets. Phenol did not appear in the EPA or USLCI databases but was reported in the survey. Nitrogen oxide emissions were 48 percent less, probably because of better combustion techniques and burner design. Liquid emissions were minimal, and no liquid emissions were reported at most mills.

Regional differences

Difference in diesel use between regions was only 0.8×10^{-5} liters/$kg_{residue}$, with the variability likely due to how the fuel is moved within the mills. Diesel use is thus shown simply as 8.05×10^{-4} liters/$kg_{residue}$ in Table 4. As another example, water use ranged from 0.57 to 3.1 liters/$kg_{residue}$ in the PNW, 0.46 to 3.3 liters/$kg_{residue}$ in the SE, 1.0 to 1.7 liters/$kg_{residue}$ for plywood facilities, and 0.46 to 3.3 liters/$kg_{residue}$ for lumber facilities; water use is shown simply as 1.58 liters/$kg_{residue}$ (sum of the four values) in Table 4. Likewise, electricity use ranged from 0.025 to 0.14 kWh/$kg_{residue}$ in the PNW region and from 0.034 to 0.14 kWh/$kg_{residue}$ in the SE region; it is shown as 0.082 kWh/$kg_{residue}$ in Table 4. The differences noted between the PNW and SE regions were not significant enough to warrant separation.

LCI results for the CORRIM wood boiler, based on inputs provided by mill surveys (Table 4), compared with the USLCI wood boiler database (USLCI 2008) are shown in Table 8. Major differences between the two databases are the reporting input emissions (Table 7) and the inclusion of fuels and chemicals required to operate and maintain a boiler (Table 4), which were reported in the CORRIM wood boiler survey.

Table 8.—Life cycle inventory results for the Consortium for Research on Renewable Industrial Materials (CORRIM) wood boiler and US Life Cycle Inventory database (USLCI 2008) wood boiler.[a]

	Values ($kg_{emission}/kg_{residue}$)	
Air emissions	CORRIM wood boiler, 2012	USLCI (2008)
Acetaldehyde	1.04E−06	7.47E−06
Acrolein	7.96E−07	3.60E−05
Aldehydes: unspecified	6.94E−08	0.00E+00
Ammonia	1.46E−05	0.00E+00
Carbon dioxide, biogenic	1.73	1.73
Carbon dioxide, fossil	6.15E−02	0.00E+00
Carbon monoxide, biogenic	3.17E−03	0.00E+00
Carbon monoxide, fossil	6.51E−05	5.40E−03
Dinitrogen monoxide	2.24E−07	0.00E+00
Formaldehyde	1.24E−05	3.96E−05
HAP	6.16E−06	0.00E+00
Hydrogen chloride	1.22E−05	1.71E−04
Isoprene	8.97E−06	0.00E+00
Methane	1.61E−04	1.89E−04
Methane, biogenic	2.19E−05	0.00E+00
Methane, fossil	1.83E−05	0.00E+00
Methanol	7.80E−06	0.00E+00
Naphthalene	5.69E−08	8.73E−07
Nitrogen monoxide	2.87E−06	0.00E+00
Nitrogen oxides	1.26E−03	2.10E−03
NMVOC, unspecified origin	4.58E−06	0.00E+00
Particulates, <10 μm	4.63E−04	0.00E+00
Particulates, <2.5 μm	1.39E−04	0.00E+00
Particulates, >10 μm	2.50E−06	0.00E+00
Particulates, >2.5 μm and <10 μm	5.66E−06	4.50E−03
Particulates, unspecified	3.08E−05	0.00E+00
Phenol	6.10E−07	0.00E+00
Propanal	5.05E−08	0.00E+00
Sulfur dioxide	5.23E−04	0.00E+00
Sulfur oxides	1.29E−05	0.00E+00
VOC	8.67E−04	0.00E+00
Wood (dust)	5.52E−04	0.00E+00

[a] Results include all upstream processes for ancillary materials (fuels, oils, chemicals, etc.) for boiler operations. HAP = hazardous air pollutant; NMVOC = nonmethane volatile organic compound; VOC = volatile organic compound.

LCIA results

Life-cycle impact assessment (LCIA) establishes links between the LCI results and potential environmental impacts and calculates impact indicators, such as GWP and smog. These impact indicators provide general but quantifiable indications of potential environmental impacts. Environmental impacts are determined using the TRACI method (Bare et al. 2011). Results for GWP, acidification, eutrophication, ozone depletion, respiratory effects, and smog are shown in Figure 2. For GWP, all carbon dioxide, including that from biomass and fossil, is included in these results. Carbon dioxide emissions from wood combustion are the same for both the CORRIM boiler and the USLCI boiler. The difference is in the fuel and chemical inputs for operating and maintaining a wood boiler. The previous databases did not include materials, fuels, chemicals, and electricity, as listed in Table 4. These accounted for an increase in GWP of about 2 percent for the CORRIM wood boiler. In all other impact categories, values for the CORRIM wood boiler were less than for the USLCI boiler. These follow the reductions in individual emissions listed in Table 7.

The greatest reductions in impacts were for ozone, eutrophication, and respiratory effects. All substances that contribute to ozone depletion were present in the CORRIM wood boiler data, while only one was present in the previous USLCI database (methane, tetrachloro-, chlorofluorocarbon-10). For the CORRIM wood boiler, this substance was lower by 100 percent and occurred in the manufacture of fuels and chemicals; in the USLCI wood boiler, this substance was reported as a result of combustion of the type of "wood" fuel used. Particulates, ammonia, carbon monoxide, and sulfur oxides are the substances that contribute to respiratory effects. All of these substances were present for the CORRIM wood boiler, and most were from the fuel and chemical input processes, which were absent the USLCI database. Of the emissions that overlapped (carbon monoxide, nitrogen oxides, particulates <10 μm), there were reductions of from 40 to 100 percent. The only emission to water that showed a reduction was BOD5 (biological oxygen demand). This

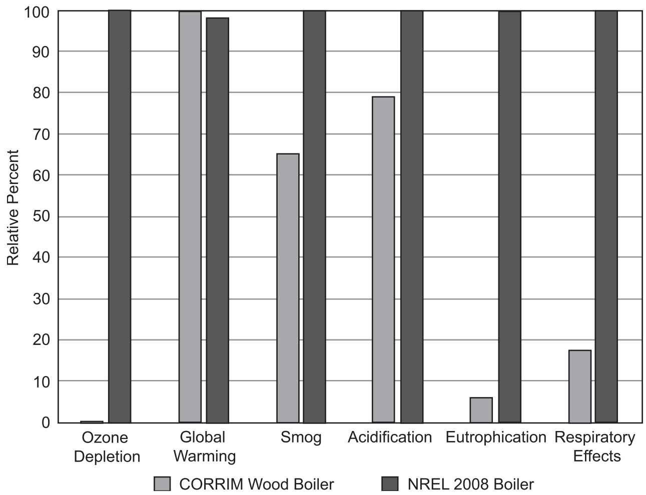

Figure 2.—Environmental impact assessment differences of selected impact categories between the Consortium for Research on Renewable Industrial Materials wood boiler and the US Life Cycle Inventory wood boiler.

emission represented 90 percent for this impact category in the USLCI database, while for the CORRIM database, it represented less than 1 percent. Nitrogen oxides were the largest contributors to eutrophication in the CORRIM boiler, representing 93 percent.

Conclusions

The material inputs and outputs for the CORRIM boiler should be a good representation of what occurs at an industrial wood boiler at wood production facilities. The survey requested actual emissions and therefore should be a better representation of wood boilers than previous data, which represented the potential to emit. If the model inputs include upstream impacts, then a cradle-to-gate LCI for wood combustion in an industrial boiler can be done. Similarly, the model can be used for cradle-to-gate LCIs of wood products when energy from a wood boiler is used in the processing.

Results indicated that regional differences, as well as type of wood waste burned, did not warrant separate boilers for facilities producing different wood products. Twenty-two emissions were reported by these industries, with 13 overlapping with previously published data sets. Survey emissions were lower (from 40% to 99%) than those reported in previously published data sets, with the exception of phenol, which was higher by 35 percent. Nine survey emissions were not reported in previous data sets, while 17 emissions previously reported were not reported in surveys. Based on the extent of this survey and the quality of data collected, the boiler emission factors presented in this article are a better representation of wood-combusted boilers used in wood production facilities in the United States.

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