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Life-cycle Inventory of Wood Pellet Manufacturing in Wisconsin

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Abstract

The purpose of this study was to determine the environmental impacts of "premium" wood pellets manufactured in Wisconsin through a cradle-to-gate life-cycle inventory. The system boundary began with growing and harvesting timber and ended with product (wood pellets) leaving the mill complex. The functional unit was the mill complex, which produces wood pellets from a variety of feedstocks. Three groups of pellet manufacturers were identified based on feedstock: those who utilize green co-product (>35% moisture on a wet basis), those who utilize dry co-product (<35% moisture on wet basis), and those who harvest their own timber. Some mills utilize a combination of feedstocks using processing steps including log and/or co-product handling, chipping, hammer milling, drying, and pelletization. The mill data was weight averaged on a per unit basis of 1.0 short ton of "premium" wood pellets, and the burdens for all substances and energy were allocated among the products on a wet mass basis. Using the LCI modeling software package SimaPro 7.2, environmental impacts were measured based on emissions to air and water, solid waste, energy consumption, and resource use. Results indicate that the majority of fuel consumed on-site in the manufacturing of wood pellets is green wood fuel (~65%), followed by electricity (~32%). On-site energy consumption for producing wood pellets from source-dried co-product was ~65% less than using co-product dried in-situ and producers who harvest their own timber. However, when considering the cradle-to-gate material and energy inputs, wood pellets produced from whole logs harvested by the manufacturer use 32-35% less energy and have a much lower environmental impact.

INTRODUCTION

Wood Pellet Fuel

In the long view of American history, wood served as the preeminent form of energy for about half of the nation's history. This trend faded as the extraction of fossil fuels for energy production intensified, but regained interest whenever fossil fuel costs rose sharply. Direct combustion for space heating is by far the most efficient way to extract energy from wood as modern stoves can realize over 95% efficiency (USDA, 2009). Wood, as it exists in the forest, is not cost effective as a main fuel source due to its low energy density, low bulk density, and the fact that it is 50% water by weight. However, once the wood is dried and densified through the pelletization process, the energy content per unit volume approaches that of coal and allows for more economical shipping (USDA, 2009).

The Pellet Fuels Institute (PFI) is a non-profit organization that establishes and maintains densified biomass fuel standards allowing pellet fuel manufacturers to become certified, provided that their fuel passes a quality assurance test. This quality assurance test analyzes fuel pellet properties including fines content, bulk density, diameter, length, chloride, moisture content, pellet durability and inorganic ash content. This system of quality standardization allows for consumers of pelletized biomass fuels to utilize means of automated feeding for heating appliances rather than manual feeding as with firewood (PFI, 2010).

Wood Pellet Production

The total wood pellet production capacity for North America in 2008 was 4.6 million tons while actual production was just over 3.5 million tons (USDA, 2009). In 2009, North America produced about 7 million tons of wood pellets, with almost 5 million tons intended for export to Europe (Pirraglia et al, 2010). In the U.S., 80 percent of the wood pellets produced are consumed domestically. This trend is reversed in Canada, the largest exporter of wood pellets in the world, where almost 90 percent of its production is intended for the export market (USDA, 2009). Wood pellet production in the United States tends to be centered near the largest sources of wood residue from primary woodworking plants, such as sawmills and plywood mills, and secondary woodworking plants, like furniture and millwork factories. The South accounts for the largest share of pellet production (46%), followed by the Northeast (24%), the West (16%), and the Midwest (14%) (USDA, 2009).

In Wisconsin, as well as the rest of the U.S., wood pellets are primarily utilized for residential heating. In 2008, wood accounted for 4.3% of Wisconsin's residential space heating needs, behind natural gas (66.4%), electricity (12.7%), liquid petroleum gas (11.1%), and fuel oil (4.4%) (WOEI, 2010). Although fossil fuels are still the dominant residential heating fuel, wood use increased by 70% from 2000 to 2008 (WOEI, 2010). In 2006, Wisconsin adopted a renewable portfolio standard that requires utilities to produce 10 percent of their electricity from renewable sources by 2015. Biomass fuels are just one of the renewable fuel options the state is looking into to achieve this goal. Others include solar, wind, hydroelectric power, geothermal technology, tidal or wave action, and fuel cell technologies that use qualified renewable fuels. As more attention is paid to greenhouse gases and other emissions associated with fossil fuel combustion, the U.S. is looking to Europe as a model for large scale energy production from pellet fuels.

Life-Cycle Inventory

The purpose of this study was to find the environmental impacts of “premium” wood pellets manufactured in Wisconsin through a cradle-to-gate life-cycle inventory (LCI). The U.S. EPA (2006) defines life-cycle inventory as “a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life-cycle of a product, process, or activity.” This cradle-to-gate LCI for wood pellets provides measures of all inputs and outputs for every stage of processing from forest regeneration, harvesting, transportation, energy production, wood processing, and pellet manufacturing. Cradle-to-grave LCI would also include use distribution, combustion, and ultimate disposal of all materials. A life-cycle assessment (LCA) tracks a product's environmental impact from resource extraction through disposal and examines both the energy inputs and the pollution outputs (NREL, 2010). LCI data must first be analyzed before an LCA can be conducted to answer environmental impact questions and identify areas for improvement. The quality of an LCA, which was beyond the scope of this study, depends on the LCI data it uses.

NREL and CORRIM

The Consortium for Research on Renewable Industrial Materials (CORRIM) was formed at the University of Washington in 1998 with the following objectives: 1.) developing a database and modeling system for environmental performance measurements associated with materials use and, 2) responding to specific questions and issues related to environmental performance and the cost effectiveness of alternative management and technology strategies (CORRIM, 2010). For over a decade, CORRIM has developed LCAs for alternative materials and designs for building construction and use and has developed International Organization of Standards (ISO) consistent research protocols to create a universal database for LCI data. These data are made publicly available by the U.S. Department of Energy in the National Renewable Energy Laboratory (NREL) U.S. LCI database (NREL, 2010). It should be noted that following submission of a final report to CORRIM, data collected during this study will be critically reviewed following the ISO 14048 project data review protocol and incorporated into the U.S. LCI database.

Scope of Study

The functional unit of the current study is the pellet mill complex, which includes handling delivered logs and processed wood fiber, size reduction, drying, generating steam for drying, pelletizing, cooling, and packaging of the final product. The system boundaries are defined according to established CORRIM protocol and all substances and energy are allocated to the products and co-products on a wet mass basis.

Methods

Unit Processes

Data was collected using a unit process approach to ensure that only information directly relevant to the scope of the LCI was requested. For the survey, wood pellet production was broken down into four unit processes: whole log or co-product receiving/handling, size reduction, drying, and pelletization. These are described as follows:

1. **Receiving/Handling**. The system boundary for this unit process encompasses the transportation of raw materials to the pellet mill, the whole log or co-product storage area and the equipment used to sort the various feedstock. The main inputs are hardwood whole logs and co-products from a primary wood product facility. The outputs are wet or

dry large wood feedstock: pulp chips, bark, sawdust, and hog fuel. The following occur within the boundary:

- transportation of logs and co-product feedstock to the pellet mill,
- in-yard conveyance of logs from the point of unloading to the deck,
- sorting and storage of logs,
- in-yard conveyance of logs from the deck to the chipper or debarker,
- debarking of logs,
- breakdown of logs into pulp chips, bark and sawdust, and
- in-yard conveyance of chipped logs and purchased co-products.

2. **Size Reduction**. The system boundary for this unit process encompasses the chipper, hogmill, and hammermill equipment, as well as the equipment used to transport the feedstock. The main input is mixed wood feedstock. The output is wet or dry sawdust. The following occur within the boundary:

- conveyance of feedstocks from piles to mills,
- mixing of various feedstocks, and
- treatment of process air, liquids and solids.

3. **Drying**. The system boundary for this unit process encompasses the dryers, loading area, and unloading/cooling areas. The main input is wet wood feedstock (20-50% moisture). The output is dry wood feedstock (12-17% moisture). The following occur within the boundary:

- loading of green feedstock into the driers,
- drying of feedstock inside the driers, and
- treatment of process air, liquids and solids.

4. **Pelletization**. The system boundary for this unit process encompasses the pellet mills and packaging areas. The main input is dry sawdust. The outputs are premium wood pellets in bags. The following occur within the boundary:

- conveyance of dry sawdust to pellet mills,
- cooling of the compressed wood pellets,
- conveyance of wood pellets to bagging equipment,
- bagging and preparation for shipping of premium wood pellets, and
- treatment of process air, liquids and solids.

Based on the type of the wood fiber used as feedstock, three production scenarios were identified for Wisconsin wood pellet production. Some wood pellet manufacturers harvest and process their own timber as feedstock. Other wood pellet manufacturers purchase green, non-dried co-products (MC > 35%) or pre-dried co-products (MC < 35%) from primary wood processing facilities for feedstock. Actual wood pellet manufacturers may use a combination of these materials to produce pellets, but the distinction is made to better understand the environmental consequences of each wood pellet production scenario.

System Boundaries

Boundary selection is important because the material and energy that cross this boundary must be accounted for through the LCI (Figure 1). CORRIM (Wilson and Sakimoto, 2005) defines two boundaries used to track the environmental impact of producing wood products. One is the total (cumulative) system boundary (solid line in Figure 1), which includes both on-site and off-site emissions for all material and energy consumed. The on-site system boundary (dotted line in Figure 1) includes the environmental impacts and emissions at the pellet mill complex from the four individual unit processes described previously.

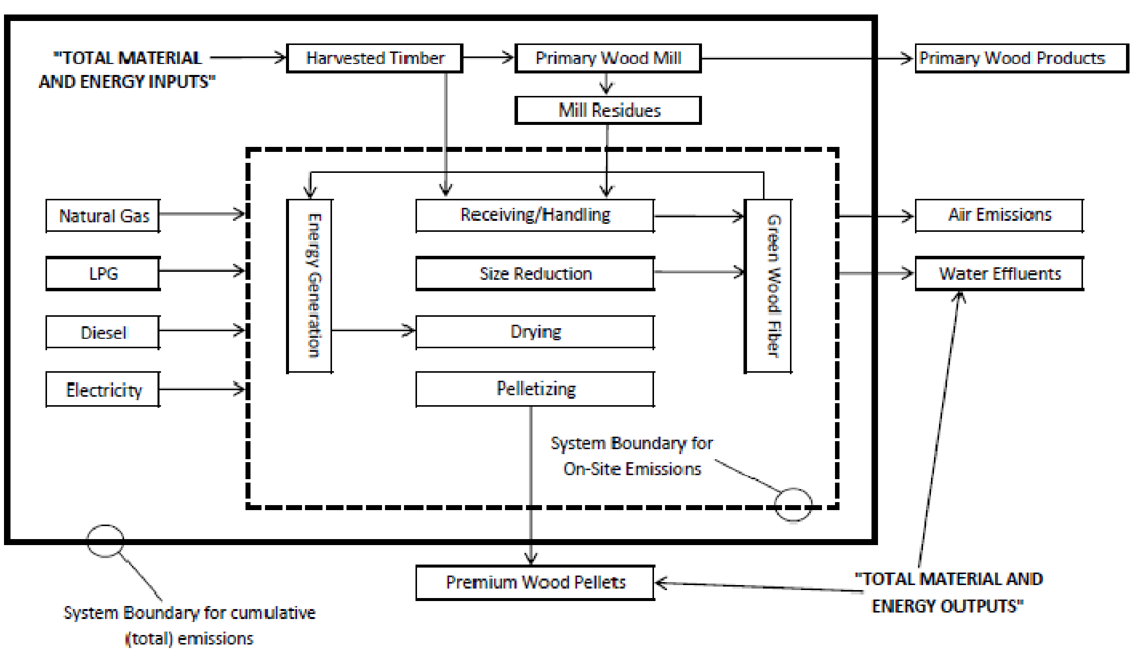

Figure 1. System boundaries for wood pellet production

Mill Survey

A questionnaire was developed to specifically address the production of wood pellet fuel. Initially, a draft questionnaire was distributed to all pellet producing facilities in Wisconsin and critically reviewed by representatives from four pellet mills. The pre-tested questionnaire was then adjusted to accommodate the privacy needs of the respondents. A total of four large-scale pellet mills from three companies completed the questionnaire and provided detailed data about the inputs and outputs to their operations for the 2009 calendar year. Average annual production for the mills that completed the survey was 27,550 tons with a range of 20,000 to 35,630 tons. For the purposes of this study, annual production for a large-scale wood pellet mill was considered to be 20,000 tons or more. It should be noted that representatives from each mill contributed a substantial amount of time completing the questionnaire and answering follow-up questions.

Total large scale production of premium wood pellets in Wisconsin in 2009 was determined to be approximately 180,000 tons. The four mills surveyed produced 110,213 tons of premium wood pellets in 2009. With 61% of Wisconsin's total 2009 wood pellet production included in the survey, this exceeded the minimum CORRIM protocol guideline for data representation (ISO 1998). Two of the mills produced premium wood pellets from a combination of self-harvested timber and primary mill residues and the other two pellet mills used only primary mill residues. It should be noted that in addition to pellet fuel, many of the large-scale wood pellet production facilities also produced other products such as animal bedding and commercial wood chips.

Existing Data

LCI data from CORRIM and NREL, which was already included in the U.S. LCI database, was utilized in order to model the off-site timber production, timber harvesting, and primary wood production processes. Timber harvest and primary hardwood and softwood forest products and co-product LCI data were available on a regional scale; the Northeast/North Central region was completed by Hubbard and Bowe in 2008 and Bergman and Bowe in 2008 and 2009 as part of the CORRIM Phase II Final Report. Energy production data was also completed by CORRIM on a regional scale. Average composition of off-site electrical generation was found for the NE/NC region by totaling the amount of the different fuel sources for each of the 20 states in thousand kWh and calculating the percentages (USDOE 2006). On-site emissions data were obtained through Air Emissions Inventory Summary Reports from the Wisconsin Department of Natural Resources Bureau of Air Management.

Model Development

Data from the mill questionnaire were weight-averaged through the following equation, which follows protocol from previous CORRIM reports (Milota et al 2004):

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

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

In accordance with previous CORRIM life-cycle projects, the LCI modeling software SimaPro 7.2 was chosen to generate air, water, and land emission data for production scenarios based on data from the USLCI database and manufacturer surveys. The software follows the ISO 14040 protocols related to environmental management and uses a unit process approach that allows for the tracking of environmental burdens associated with each individual unit process. Survey data were modeled in SimaPro 7.2 to find non-wood raw material use and emission data. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2), a computer program developed by the U.S. Environmental Protection Agency and featured in SimaPro 7.2, allows for the characterization of stressors that have potential environmental effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria–related effects, human health cancer effects, human health non-cancer effects, fossil fuel depletion, and land-use effects (PRE, 2008). Only the global warming characterization will be discussed in this report, but further explanation of these characterization categories can be found in Bare, et al (2003).

Results

On-site air emission data for the production of premium wood pellets are found as weighted averages, which are summarized in Table 1.

Table 1. On-site emissions associated with producing one ton of premium wood pellets based on the 2009 Wisconsin industry average.

Emissions (On-Site) per ton premium wood pellets output		Wisconsin Average
Air Emissions		Weighted Average
CO	lbs	1.185
NOx	lbs	0.337
PM	lbs	3.526
PM10	lbs	3.297

Ozone	lbs	0.010
Acetic Acid	lbs	0.217
Acrolein	lbs	0.010
Formaldehyde	lbs	0.009
Xylene, M-AL	lbs	0.004
Acetaldehyde	lbs	0.012
VOC (ROG)	lbs	1.33

All on-site raw material, fuel, and energy inputs reported from the mill surveys are summarized in Table 2 on a per ton of premium wood pellet production basis. This table represents a weighted average of survey data, rather than data for any one mill. Production scenarios were separated based on the type of feedstock used and raw material data is provided on a wet basis. A weighted Wisconsin average was also calculated to show the most common trends in raw material and energy usage scenarios during the survey period. Feedstock and total energy percentages are listed to identify the most significant inputs. To convert volume or mass basis of a fuel to its energy value (BTU), higher heating values (HHV) were used. HHV represents the energy content of a fuel with the combustion products, such as water vapor, brought to 25ºC (77ºF) while the lower heating value (LHV) ignores the energy produced by the combustion of hydrogen in fuel.

A summary of the cradle-to-gate fuel and energy requirements for producing one short ton of Wisconsin wood pellets is provided in Table 3. The data listed in Table 3 represent the growing and harvesting of the timber, as well as the processing of the lumber at primary forest products mills, and the production of wood pellets. Air and water emissions characterizations were performed for the three production scenarios using TRACI 2 (Figure 2 and Table 4). A complete cradle-to-gate LCI tracking material and energy inputs as well as air and water emission outputs for each production scenario can be found in Appendices A, B, and C, with all materials and emissions data are provided on a per ton premium wood pellets production basis.

Table 2. All raw material, fuel, and energy inputs used on-site at Wisconsin wood pellet manufacturing facilities per ton of premium wood pellet output in 2009. Three raw material feedstock scenarios and a representative average of all mills for the state are presented along with total on-site energy consumption.

On-Site Inputs per Short Ton Premium Wood Pellets Output	Wood Pellets from Whole	Wood Pellets from Wet Co-	Wood Pellets from Dry Co-	Wisconsin Average

		Logs	Product	Product		
Raw Materials		Weighted Average	Weighted Average	Weighted Average	Weighted Average	Feedstock %
Standing Timber (Hardwood)	m3	1.57	-	-	0.45	23.21
Standing Timber (Softwood)	m3	0.54	-	-	0.15	5.16
Wet Feedstock (Hardwood)	kg	-	1022.94	-	128.48	7.06
Wet Feedstock (Softwood)	kg	-	797.78	-	100.20	5.50
Dry Feedstock (Hardwood)	kg	-	-	917.66	542.06	59.07
Fuel Usage (On-Site)						BTU %
Electricity	kWh	200.66	176.42	143.01	163.56	31.60
Diesel	Liters	3.38	3.12	0.82	1.83	3.58
Natural Gas	Liters	0.07	0.07	0.03	0.05	0.08
LPG	Liters	0.18	0.18	0.14	0.16	0.21
Wood Fuel	kg	293.64	293.64	-	120.19	64.52
Fuel Energy Used On-Site	**BTU**	**3,591,081**	**3,499,737**	**520,443**	**1,765,782**	100
Energy Consumption (On-Site)						BTU %
Non-Renewable Fuel						
Coal	BTU	1,703,017	1,497,447	1,221,408	1,386,998	40.43
Natural Gas	BTU	280,987	247,331	196,307	227,305	6.63
Crude oil	BTU	269,737	243,451	127,711	182,539	5.32
Uranium	BTU	607,105	533,819	376,107	494,459	14.41
Renewable Fuel						
Wood	BTU	2,783,675	2,783,675	-	1,139,358	33.21
Total Energy Consumption	**BTU**	**5,644,521**	**5,305,723**	**1,921,534**	**3,430,660**	100

Table 3. Cradle-to-Gate fuel and energy consumption required for producing one short ton of premium grade wood pellets in Wisconsin in 2009.

Cradle-to-Gate Energy Inputs per Short Ton Premium Wood Pellet Output		Wood Pellets from Whole Logs	Wood Pellets from Wet Co-Product	Wood Pellets from Dry Co-Product	WI Weighted Average	
TOTAL FUEL CONSUMPTION		Weighted Average	Weighted Average	Weighted Average	Weighted Average	BTU %
Electricity	kWh	200.66	281.72	329.56	286.98	17.12
Diesel	Liters	11.06	15.17	13.39	12.96	7.81
Gasoline	Liters	0.14	0.52	0.74	0.54	0.29
Natural Gas	Liters	0.18	43.35	51.35	35.83	18.18
LPG	cm3	0.18	183.63	140.18	105.92	0.04
Fuel Wood (50% MC)	lb	645.77	661.20	648.86	649.53	51.11
Diesel Transportation	t*mi	64.22	137.94	112.75	102.14	5.45
Fuel Energy Used	**BTU**	**4,177,529**	**6,159,027**	**6,366,365**	**5,719,351**	100
TOTAL ENERGY CONSUMPTION						
Non-Renewable Fuel						
Coal	BTU	1,716,844	2,802,319	2,824,701	2,507,591	22.26
Natural Gas	BTU	301,693	1,292,441	1,285,213	1,007,096	8.94
Crude Oil	BTU	685,850	1,261,074	1,258,983	1,096,648	9.73
Uranium	BTU	611,894	999,296	873,875	815,304	7.24
Renewable Fuel						
Wood	BTU	5,804,165	5,957,243	5,831,899	5,839,774	51.83
TOTAL	**BTU**	**9,120,447**	**12,312,374**	**12,074,671**	**11,266,413**	100

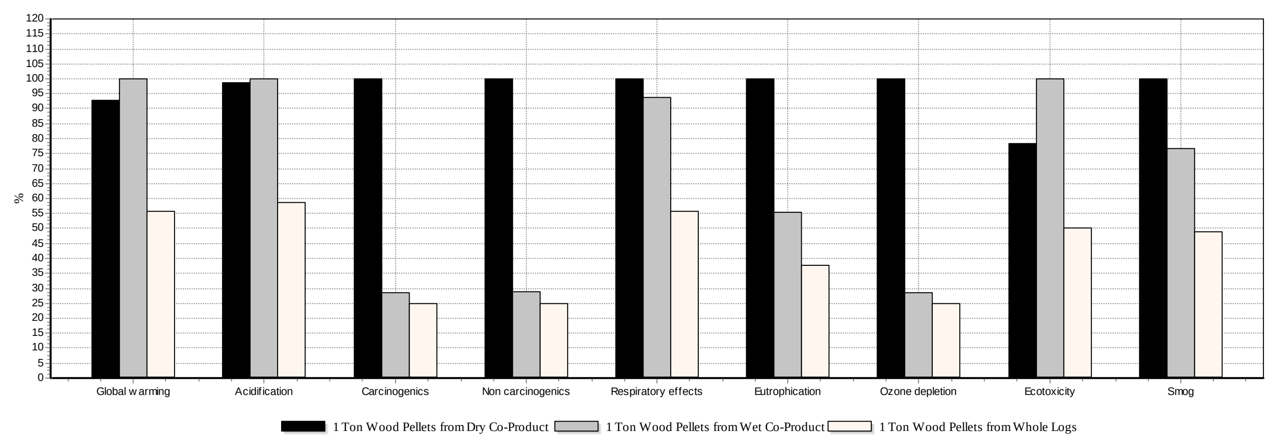

Figure 2. TRACI 2 characterization of air and waster emissions associated with the production of one ton of premium grade wood pellets from three different feedstocks.

Table 4. TRACI 2 characterization for specific air and water emissions associated with producing one ton of premium wood pellets in WI using various feedstocks.

Impact category	Unit	Wood Pellets from Whole Logs	Wood Pellets from Wet Co-Product	Wood Pellets from Dry Co-Product	WI Weighted Average
Global warming	kg CO2 eq	242.21	433.30	401.93	**360.56**
Acidification	H+ moles eq	133.45	227.06	223.94	**198.66**
Carcinogenics	kg benzen eq	349.24	399.72	1,394.28	**972.89**
Non carcinogenics	kg toluen eq	386,643	443,068	1,542,313	**1,076,384**
Respiratory effects	kg PM2.5 eq	0.34	0.57	0.61	**0.53**
Eutrophication	kg N eq	0.14	0.21	0.38	**0.29**
Ozone depletion	kg CFC-11 eq	2.19E-05	2.51E-05	8.78E-05	**6.12E-05**
Ecotoxicity	kg 2,4-D eq	19.35	38.49	30.11	**28.11**
Smog	g NOx eq	2.44	3.83	5.01	**4.13**

Discussion

Raw Materials

The average ton of premium wood pellets produced in Wisconsin in 2009 was produced mostly from source-dried hardwood co-products (59.17%), followed by primarily hardwood whole logs (28.37%), and a mixture of green hardwood and softwood co-products (12.56%). Wisconsin pellet mills producing one ton of wood pellets from self-harvested timber use an average of 1.57 m^3 of hardwood whole logs and 0.54 m^3 of softwood whole logs. Mills producing one ton of pellets from green co-product use an average of 1,022.94 kg of hardwood primary mill resides and 797.78 kg of softwood primary mill residues. Pellet mills utilizing source-dried co-products to produce one ton of wood pellets use an average of 917.66 kg of dry residue to accomplish this. Whole log feedstock is approximately 50% water by weight and has the additional weight of bark attributed to it. Green co-product feedstock is generally received by the pellet mill with a moisture content of 40-50%.

Fuel and Energy Consumption

The on-site energy consumption for the production of premium wood pellets was lowest using source-dried co-product (1,921,534 BTUs), followed by green co-product (5,305,723 BTUs), and whole logs (5,644,521 BTUs). Renewable wood fuel accounted for the majority of on-site fuel use and was primarily utilized in the biomass drying process. Of course, receiving the feedstock pre-dried eliminated the need for such an energy consumptive process. Electricity accounted for a third of on-site fuel consumption and was primarily used for fans, conveyors, air emission reduction equipment, and the pelletization process. Natural gas and wood fiber were utilized for building heat and for drying green feedstock. The weighted average on-site energy consumption for Wisconsin pellet producers was 3,430,660 BTUs.

In keeping with the nature of LCI, the combustion of the fuel does not truly reflect the entire energy consumption in the manufacturing process, as the energy required to produce and transport the fuels themselves must also be accounted for in the calculations. Cradle-to-gate energy consumption for the production of premium wood pellets was lowest using whole logs (9,120,447 BTUs), followed by source-dried co-product (12,074,671 BTUs), and green co-product (12,312,374 BTUs). The weighted average energy consumption for producing one ton of premium wood pellets in Wisconsin was 11,266,413 BTUs.

The largest contributing factor to overall fuel consumption was the amount of processing a feedstock received during primary production. Lumber mills typically dry rough sawn lumber using heat from combusting wood fuel and natural gas. It should be noted that the more than 50% of the overall fuel consumption was from wood biomass. After wood fuel consumption for drying, electricity and natural gas were the next largest contributors to overall fuel consumption. Coal was the largest source of non-renewable energy used off-site because most electricity in the northeastern United States comes from coal-fired power plants. Differences in the harvest and processing of softwoods and hardwoods also accounted for some variation between feedstock scenarios. Additional factors such as higher initial wood MCs, denser wood, and longer, slower kiln-drying schedules all contributed to higher primary manufacturing energy consumption (Puettman et al, 2010).

The gross energy content of one ton of premium wood pellets is approximately 16,400,000 BTUs. Therefore, the energy return on investment (EROI) values, or the quantity of energy supplied by pelletized wood fuel divided by the energy consumed in production, for the various feedstocks were as follows: dried co-product (1.36); green co-product (1.33); whole logs (1.80); and the Wisconsin weighted average (1.46). These values consider all materials and energy invested into producing wood pellet fuel. Therefore, if a comparison is to be made with other fuels, the methods and assumptions must consider the production inputs as thoroughly as they were considered for this study.

Global Warming Characterization

The production of one ton of premium wood pellets in Wisconsin accounted for greenhouse gas emissions equivalent to 360.56 kg of CO_2. Producing one ton of wood pellets from dry co-products released 401.93 kg CO_2 eq of greenhouse gases into the atmosphere. Using green co-products to produce one ton of wood pellets releases 433.30 kg CO_2 eq of greenhouse gases and using whole logs releases 242.21 kg CO_2 eq. A significant portion of these emissions were due to the burning of coal to produce electricity, as 58.0% of total electrical utility power provided in the Northeastern US is produced by the combustion of coal (USDOE, 2006). Methane (CH_4) is also emitted during the production and distribution of natural gas and petroleum, and is released as a byproduct of coal mining and incomplete fossil fuel combustion (USEPA, 2007).

The “greenhouse effect” refers to the process of water vapor, carbon dioxide (CO_2), and other trace gases in the atmosphere absorbing the terrestrial radiation, essentially trapping heat energy inside our atmosphere (IPCC, 2007). A way to gauge the changes in the atmospheric concentrations of these greenhouse gases is called radiative forcing, which is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the earth-atmosphere system (USEPA, 2007). Increases in greenhouse gas concentrations in the atmosphere will produce positive radiative forcing, or a net increase in the absorption of energy by the earth (USEPA, 2007).

The global warming potential (GWP) represents how much a given mass of a chemical contributes to global warming over a given time period compared to the same mass of carbon dioxide (USEPA, 2007), with carbon dioxide's GWP being 1.0. Global warming potential is a quantified measure of the globally averaged relative radiative forcing impacts of a particular greenhouse gas and is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas; in this case, CO_2 (IPCC, 2007). Direct radiative effects occur when the gas itself absorbs radiation. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are greenhouse gases, or when a gas influences other radiatively important processes such as the atmospheric lifetimes of other gases (USEPA, 2007).

Conclusion

Based on the results of the pellet industry survey, Wisconsin wood pellets are primarily produced from source-dried hardwood residues (~59%) and whole logs (~28%). On-site energy consumption using source-dried feedstock is approximately 65% less than using whole logs or green co-product feedstock. However, when considering all cradle-to-gate energy inputs, producing wood pellets from whole logs uses the least amount of energy. Pellet production from dry co-product and wet co-product used 32% and 35% more energy, respectively. An argument could be made that the co-products generated during the production of these primary wood products are waste products, would be destined for a landfill, and should not carry a portion of the energy burden associated with creating the primary wood products. However, the co-products used in pellet production are currently a valued commodity and this study is strictly focused on allocating all energy and materials associated with producing these feedstock materials, which is consistent with previously established CORRIM protocols. It should be noted that over 50% of the energy used to produce wood pellet fuel comes from wood fuel, which is a renewable source of energy. Once a more comprehensive cradle-to-grave LCI is completed, the true carbon and energy savings attributed to forest re-growth and sequestration can be realized.

A large amount of the environmental emissions associated with wood pellet production in Wisconsin can be attributed to the production of electricity from coal burning power plants. Increasing on-site wood fuel consumption would reduce fossil greenhouse gas emissions, but increase other emissions, especially particulates. Based on the results of the LCI, drying with heat produced by the combustion of biomass already accounts for a significant amount of environmental emissions. It should be noted that increasing the level of air drying for lumber prior to kiln drying would lower the amount of energy required for the drying process at the primary wood production facilities. Increasing air drying would therefore also lower energy use at the pellet mill.

The information contained in this LCI report can only be fully utilized once the life-cycles of competing renewable fuels, as well as fossil fuels, have been inventoried and analyzed to the same degree. LCA is a powerful tool for comparing various fuel options and allowing for reasonable and informed decisions. The importance of a “level playing field” for these comparisons is crucial, and should always be considered before accurate judgments can be made. LCIs are currently being developed for additional biomass-based fuels in different regions of the United States by CORRIM researchers through a grant from the Department of Energy and should be available in 2011.

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Appendices

Appendix A. Cradle-to-gate LCI for producing one short ton of premium grade wood pellets in Wisconsin in 2009 using WHOLE LOG feedstock.

Cradle-To-Gate Life Cycle Inventory for Producing One Ton of Premium Wood Pellets from Whole Logs		Producing One Ton Wood Pellets at Pelletmill	Growth and Harvest of Timber	Diesel Transport from Forest to Pelletmill	Total
INPUTS					
Carbon dioxide, in air	kg	3.0594045	2084.707717	0.006269413	2087.7734
Coal, 26.4 MJ per kg, in ground	lb	151.24408	0.903781322	0.31140762	152.45927
Gas, natural, in ground	cuft	272.80263	14.93339695	5.1454632	292.88149
Occupation, forest, intensive, normal	m^2a	x	6512.768442	x	6512.7685
Oil, crude, in ground	oz	220.45592	271.3030646	93.4804	585.23938
Uranium oxide, 332 GJ per kg, in ore	g	1.6797248	0.009751179	0.003359874	1.6928358
OUTPUTS					
Air Emissions					
2-Chloroacetophenone	ng	101.63196	0.605805719	0.20873691	102.4465
5-methyl Chrysene	ng	656.80256	3.950869403	1.3613147	662.11474
Acenaphthene	µg	15.225489	0.091586022	0.031556953	15.348632
Acenaphthylene	µg	7.4636895	0.044896386	0.015469535	7.5240554
Acetaldehyde	g	6.0417685	0.104124892	2.30E-05	6.1459164
Acetic acid	g	98.548079	x	x	98.548079
Acetophenone	ng	217.78276	1.298155132	0.44729337	219.52821
Acrolein	g	7.1980714	0.012609626	2.07E-05	7.2107018
Aldehydes, unspecified	mg	283.03703	312.5887785	107.70584	703.33165
Ammonia	mg	280.15589	157.110485	54.134116	491.4005
Ammonium chloride	mg	89.153437	0.517555693	0.1783294	89.849322
Anthracene	µg	6.269515	0.037713058	0.012994441	6.3202225
Antimony	mg	5.7568285	0.003232537	0.001113805	5.7611749
Arsenic	mg	27.172291	0.105111157	0.036217184	27.313619
Benzene	g	2.8685671	0.126922212	0.000117628	2.995607
Benzene, chloro-	ng	319.41472	1.903960906	0.65603027	321.97471
Benzene, ethyl-	µg	1.4586381	0.008135105	0.002803038	1.4695762
Benzo(a)anthracene	µg	2.3883489	0.014366656	0.004950186	2.4076658
Benzo(a)pyrene	µg	1.1344852	0.006824275	0.002351378	1.1436608
Benzo(b,j,k)fluoranthene	µg	3.2840128	0.019754347	0.006806574	3.3105737
Benzo(ghi)perylene	ng	806.08505	4.848851993	1.6707243	812.60463
Benzyl chloride	µg	10.163196	0.060580572	0.020873691	10.24465
Beryllium	mg	1.3902364	0.005135441	0.001769472	1.3971413
Biphenyl	µg	50.753405	0.305297301	0.10519348	51.163896

Bromoform	ng	566.23518	3.375203335	1.1629628	570.77335
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	g	1.9031235	0.104178246	0.03589574	2.0431975
Butadiene	mg	2.229087	5.308266695	0.001172455	7.5385261
Cadmium	mg	4.4938539	0.025906922	0.00892651	4.5286873
Carbon dioxide, biogenic	lb	290.77596	0.040113931	0.013821688	290.8299
Carbon dioxide, fossil	lb	365.71881	54.74173446	20.344744	440.80529
Carbon disulfide	µg	1.8874506	0.011250678	0.003876543	1.9025778
Carbon monoxide	g	934.83228	0.00468268	0.001613468	934.83857
Carbon monoxide, fossil	g	166.86378	235.2893868	48.270869	450.42403
Chloride	µg	2.3446134	0.013944256	0.004804644	2.3633623
Chlorine	mg	521.94434	x	x	521.94434
Chloroform	ng	856.6122	5.106076844	1.7593539	863.47763
Chromium	mg	22.047779	0.075323276	0.025953448	22.149056
Chromium VI	mg	2.3584851	0.014187018	0.00488829	2.3775604
Chrysene	µg	2.9855022	0.017958711	0.006187868	3.0096488
Cobalt	mg	8.8247311	0.152045227	0.052388824	9.0291652
Copper	µg	56.150754	1.337785684	0.4609485	57.949488
Cumene	ng	76.949909	0.458681475	0.15804366	77.566635
Cyanide	µg	36.297127	0.216359187	0.074548895	36.588035
Dinitrogen monoxide	mg	369.35779	28.84037502	212.64899	610.84715
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	mg	1.103363	4.82956E-07	1.66E-07	1.1033637
Ethane, 1,1,1-trichloro-, HCFC-140	µg	0.87667258	0.72325281	0.24920457	1.84913
Ethane, 1,2-dibromo-	ng	17.422621	0.103852411	0.03578347	17.562257
Ethane, 1,2-dichloro-	ng	580.75403	3.461746989	1.1927823	585.40856
Ethane, chloro-	ng	609.79174	3.634834396	1.2524214	614.67899
Ethene, tetrachloro-	mg	1.3095698	0.00941444	0.003243847	1.3222281
Fluoranthene	µg	21.197022	0.127506574	0.043933767	21.368462
Fluorene	µg	27.167273	0.163419697	0.05630802	27.387001
Fluoride	mg	2.6549452	0.015412689	0.005310609	2.6756685
Formaldehyde	g	7.0862543	0.16147182	0.000472923	7.2481991
Furan	ng	141.02137	0.817620431	0.28171995	142.12071
Hexane	ng	972.76301	5.798426252	1.9979104	980.55934
Hydrazine, methyl-	µg	2.4682046	0.014712425	0.005069325	2.4879864
Hydrocarbons, unspecified	mg	514.56032	2.987138041	1.0292507	518.57671
Hydrogen chloride	g	48.595619	0.232090402	0.079969254	48.907678
Hydrogen fluoride	g	4.4775561	0.026934016	0.009280406	4.5137705
Hydrogen sulfide	ng	75.785778	0.450725165	0.15530222	76.391805
Indeno(1,2,3-cd)pyrene	µg	1.8211916	0.010955021	0.003774671	1.8359213
Isophorone	µg	8.4209335	0.050195331	0.017295344	8.4884242
Isoprene	g	76.84884	0.45704757	0.15748068	77.463368

Kerosene	mg	42.698018	0.247871563	0.085406825	43.031296
Lead	mg	44.900927	0.115236148	0.03970586	45.055869
Magnesium	mg	328.40128	1.975434697	0.68065737	331.05737
Manganese	g	1.0725954	0.000158368	5.46E-05	1.0728083
Mercaptans, unspecified	mg	3.0308507	0.017575218	0.006055731	3.0544816
Mercury	mg	4.896317	0.019900107	0.006856797	4.9230739
Metals, unspecified	g	28.258404	5.17078E-11	1.78E-11	28.258404
Methane	g	330.22867	32.18772746	11.090629	373.50703
Methane, bromo-, Halon 1001	µg	2.3230161	0.013846988	0.004771129	2.3416343
Methane, dichloro-, HCC-30	mg	201.78859	0.166215608	0.057271383	202.01207
Methane, dichlorodifluoro-, CFC-12	µg	0.72529154	0.892576702	0.30754694	1.9254152
Methane, fossil	g	16.344162	2.423093523	0.54999531	19.317251
Methane, monochloro-, R-40	µg	7.6949909	0.045868148	0.015804366	7.7566635
Methane, tetrachloro-, CFC-10	mg	29.731079	8.92577E-05	3.08E-05	29.731199
Methyl ethyl ketone	µg	5.6623518	0.033752033	0.011629628	5.7077335
Methyl methacrylate	ng	290.37702	1.730873499	0.59639116	292.70428
Naphthalene	mg	64.836442	0.031418373	0.01082554	64.878686
Nickel	mg	51.98457	1.93906648	0.66812631	54.591763
Nitrogen oxides	oz	32.659387	15.94019404	2.2110079	50.810589
NMVOC, non-methane volatile organic compounds, unspecified origin	g	18.772625	15.13857857	5.215986	39.127189
Organic acids	µg	327.61574	1.901882859	0.65531427	330.17294
Organic substances, unspecified	mg	185.11982	1.11574267	0.38444119	186.62
Ozone	g	4.5413861	x	x	4.5413861
PAH, polycyclic aromatic hydrocarbons	mg	9.5774933	22.80749383	0.005037763	32.390024
Particulates	kg	1.6012928	x	x	1.6012928
Particulates, < 10 um	kg	1.497295	x	x	1.497295
Particulates, > 2.5 um, and < 10um	g	343.91704	13.7997789	1.1261572	358.84298
Particulates, unspecified	g	101.03847	2.382409087	0.82088476	104.24176
Phenanthrene	µg	80.608505	0.484885199	0.16707243	81.260463
Phenol	ng	232.30161	1.384698805	0.47711293	234.16343
Phenols, unspecified	mg	35.326343	0.088872963	0.030622139	35.445838
Phthalate, dioctyl-	µg	1.0598761	0.006317688	0.002176828	1.0683706
Propanal	µg	5.5171633	0.032886597	0.011331432	5.5613814
Propene	mg	147.08388	350.2603958	0.07736421	497.42164
Propylene oxide	ng	85.067297	x	x	85.067297
Pyrene	µg	9.8520423	0.059263081	0.020419735	9.9317251
Radioactive species, unspecified	Bq	1688700.6	10177.64783	3506.8185	1702385
Radionuclides (Including Radon)	g	2.387708	0.01386118	0.004776019	2.4063452
Selenium	mg	40.978965	0.252116439	0.086869441	41.31795
Styrene	ng	362.97127	2.163591867	0.74548895	365.88035
Sulfur dioxide	oz	36.402997	0.446865777	0.15397243	37.003835

Sulfur oxides	g	63.482547	25.13156688	8.7895344	97.403649
Sulfuric acid, dimethyl ester	ng	696.90484	4.154096426	1.4313388	702.49028
t-Butyl methyl ether	ng	508.15978	3.029028621	1.0436845	512.23249
Tar	µg	2.6370461	0.015683458	0.005403905	2.6581335
TOC, Total Organic Carbon	g	2.7022182	x	x	2.7022182
Toluene	mg	23.3207	55.52591525	0.012271438	78.858887
Toluene, 2,4-dinitro-	ng	4.0652782	0.024232229	0.008349476	4.0978599
Vinyl acetate	ng	110.34327	0.657731938	0.22662864	111.22763
VOC, volatile organic compounds	g	615.9204	12.15421289	3.016054	631.09067
Xylene	g	1.832803	0.038692089	8.55E-06	1.8715037
Zinc	µg	37.433836	0.891857119	0.307299	38.632992
Water Emissions					
2-Hexanone	µg	304.86207	187.2704556	64.526057	556.65858
4-Methyl-2-pentanone	µg	196.21552	120.5305503	41.530103	358.27617
Acetone	µg	466.89524	286.7998919	98.820001	852.51513
Acids, unspecified	µg	49.249145	0.292902308	0.10092265	49.64297
Aluminium	g	3.143225	2.480194672	0.85457786	6.4779976
Ammonia	g	0.76859248	0.537652443	0.18525396	1.4914989
Ammonia, as N	µg	24.733419	0.147098497	0.050684376	24.931202
Ammonium, ion	mg	19.06156	0.11065663	0.038127937	19.210345
Antimony	mg	1.5198374	1.546935497	0.53301335	3.5997863
Arsenic, ion	mg	12.137731	7.863093529	2.7093138	22.710139
Barium	g	34.240298	33.9454773	11.696281	79.882055
Benzene	mg	78.325906	48.11305018	16.577871	143.01683
Benzene, 1-methyl-4-(1-methylethyl)-	µg	4.6656905	2.865983116	0.98750542	8.519179
Benzene, ethyl-	mg	4.4060186	2.706474944	0.93254517	8.0450387
Benzene, pentamethyl-	µg	3.4992798	2.14952469	0.74064195	6.3894464
Benzenes, alkylated, unspecified	mg	1.3326233	1.357073055	0.46759418	3.1572905
Benzoic acid	mg	47.363941	29.09392047	10.024625	86.482486
Beryllium	mg	0.58992429	0.437696342	0.150813	1.1784336
Biphenyl	µg	86.282263	87.86456102	30.274683	204.42151
BOD5, Biological Oxygen Demand	oz	45.60957	0.185072612	0.063768767	45.858412
Boron	mg	146.54189	90.01673825	31.016239	267.57487
Bromide	g	10.004658	6.144585975	2.1171835	18.266427
Cadmium, ion	mg	1.9871335	1.161214027	0.40010883	3.5484563
Calcium, ion	g	150.04131	92.13320683	31.745492	273.92001
Chloride	oz	59.492748	36.53706989	12.589242	108.61906
Chromium	mg	53.150339	65.40922115	22.537453	141.09701
Chromium VI	µg	223.63729	275.2182016	94.829403	593.68489
Chromium, ion	mg	15.839123	4.918359933	1.694674	22.452157
Cobalt	mg	1.0344098	0.635402567	0.21893482	1.8887472
COD, Chemical Oxygen Demand	g	14.825015	9.961410684	3.4323116	28.218738

Copper, ion	mg	27.537493	8.167785779	2.8142988	38.519577
Cyanide	µg	3.5238252	2.070811172	0.71352034	6.3081566
Decane	mg	1.3609941	0.836025031	0.28806145	2.4850806
Detergent, oil	mg	42.893667	24.10310706	8.3049858	75.30176
Dibenzofuran	µg	8.8778791	5.453373592	1.8790188	16.210271
Dibenzothiophene	µg	7.459268	4.689575156	1.6158438	13.764687
DOC, Dissolved Organic Carbon	ng	151.22688	0.899400389	0.30989812	152.43618
Docosane	µg	49.962057	30.68981354	10.574507	91.226377
Dodecane	mg	2.5822734	1.586206595	0.5465446	4.7150246
Eicosane	mg	0.71096936	0.436723365	0.15047775	1.2981705
Fluorene, 1-methyl-	µg	5.3137209	3.264065871	1.1246691	9.7024559
Fluorenes, alkylated, unspecified	µg	77.229136	78.64549505	27.098155	182.97279
Fluoride	mg	310.05557	1.799945521	0.62019065	312.47571
Fluorine	µg	39.702486	38.80759423	13.371576	91.881656
Hexadecane	mg	2.818538	1.731351821	0.59655597	5.1464458
Hexanoic acid	mg	9.8085695	6.02508393	2.0760077	17.909661
Hydrocarbons, unspecified	ng	189.22136	1.125367165	0.38775741	190.73448
Iron	g	6.9881225	4.942535887	1.7030041	13.633663
Lead	mg	23.297714	16.52541897	5.6940117	45.517145
Lead-210/kg	pg	4.851257	2.979985149	1.0267861	8.8580283
Lithium, ion	g	26.296271	1.467519144	0.50564957	28.26944
m-Xylene	mg	1.4146275	0.868945656	0.29940461	2.5829778
Magnesium	g	29.330225	18.01115828	6.205939	53.547322
Manganese	mg	588.36092	31.86472607	10.979336	631.20498
Mercury	µg	51.309631	27.26221255	9.3934898	87.965334
Metallic ions, unspecified	µg	2.3102907	0.013740126	0.004734309	2.3287651
Methane, monochloro-, R-40	µg	1.8793048	1.154396818	0.39775989	3.4314615
Methyl ethyl ketone	µg	3.7584699	2.30871253	0.79549183	6.8626742
Molybdenum	mg	1.0733078	0.65930018	0.227169	1.959777
n-Hexacosane	µg	31.169633	19.14661471	6.5971728	56.913421
Naphthalene	mg	0.84929584	0.522557001	0.18005266	1.5519055
Naphthalene, 2-methyl-	mg	0.73954757	0.454279593	0.15652694	1.3503541
Naphthalenes, alkylated, unspecified	µg	21.837046	22.23758222	7.6621989	51.736826
Nickel	mg	10.390555	7.750416604	2.6704897	20.811461
Nitrate	ng	16.577958	0.098595051	0.033971989	16.710525
Nitrate compounds	ng	667.44311	3.969523172	1.3677421	672.78038
Nitric acid	mg	1.4971029	0.008903807	0.003067903	1.5090746
Nitrogen, total	mg	47.45184	0.275468572	0.09491567	47.822224
o-Cresol	mg	1.3431549	0.825053591	0.28428113	2.4524897
Octadecane	mg	0.69632225	0.427727222	0.14737803	1.2714275
Oils, unspecified	g	1.1086599	0.661899791	0.22806472	1.9986244
p-Cresol	mg	1.4491794	0.890165429	0.30671611	2.646061

Phenanthrene	µg	9.4734833	7.971400677	2.7466322	20.191516
Phenanthrenes, alkylated, unspecified	µg	9.0545313	9.220612164	3.1770615	21.452205
Phenol	mg	9.8976826	12.17996379	4.196738	26.274384
Phenol, 2,4-dimethyl-	mg	1.3078186	0.803349926	0.2768029	2.3879714
Phenols, unspecified	mg	12.339499	2.31022667	0.79601356	15.445739
Radioactive species, Nuclides, unspecified	Bq	2768.6924	16.07287995	5.5380844	2790.3033
Radium-226/kg	ng	1.6877586	1.036760235	0.35722694	3.0817458
Radium-228/kg	pg	8.6333512	5.303145992	1.8272562	15.763753
Selenium	mg	6.9681921	0.33875629	0.11672214	7.4236705
Silver	mg	97.951099	60.24053212	20.756526	178.94816
Sodium, ion	g	475.64488	292.0678211	100.63512	868.34783
Solids, inorganic	µg	3.8063414	0.022637675	0.007800056	3.8367792
Solved solids	oz	73.384904	45.06417505	15.527348	133.97643
Strontium	g	2.5453219	1.563532581	0.53873204	4.6475865
Sulfate	g	42.054637	2.309906899	0.79590336	45.160447
Sulfide	mg	1.1487122	1.413280329	0.486961	3.0489536
Sulfur	mg	123.70216	75.9862311	26.181877	225.87027
Suspended solids, unspecified	g	83.821996	76.21850951	26.261911	186.30242
Tar	ng	37.722364	0.224348408	0.077301666	38.024014
Tetradecane	mg	1.1317083	0.695171572	0.23952887	2.0664088
Thallium	µg	320.4393	325.964614	112.31463	758.71854
Tin	mg	7.6895842	6.294554458	2.1688567	16.152995
Titanium, ion	mg	23.346013	23.7562154	8.1854607	55.28769
Toluene	mg	74.000579	45.45619089	15.662421	135.11919
Vanadium	mg	1.2678504	0.77879846	0.26834342	2.3149923
Xylene	mg	39.063833	24.41080604	8.4110067	71.885645
Yttrium	µg	314.64753	193.2812698	66.597147	574.52594
Zinc	mg	87.738005	57.31118516	19.747188	164.79638

Appendix B. Cradle-to-gate LCI for producing one short ton of premium grade wood pellets in Wisconsin in 2009 using WET CO-PRODUCT feedstock.

Cradle-To-Gate Life Cycle Inventory for Producing One Ton of Premium Wood Pellets from Wet Co-Product		Producing One Ton Wood Pellets at Pellet Mill	Producing Wet Co-Product Feedstock at Sawmill	Growth and Harvest of Timber	Diesel Transport from Sawmill to Pelletmill	Diesel Transport from Forest to Sawmill	**Total**
INPUTS							
Carbon dioxide, in air	kg	2.6901038	3.7788526	1962.79399	0.00734859	0.01346695	1969.2837
Coal, 26.4 MJ per kg, in ground	lb	132.98749	74.454119	0.90956837	0.36501131	0.66891621	209.38511
Gas, natural, 46.8 MJ per kg, in ground	g	x	3.8948627	x	x	x	3.8948627
Gas, natural, in ground	cuft	240.12673	154.77101	15.0290179	6.03117	11.052664	427.01059
Limestone, in ground	g	x	142.97597	x	x	x	142.97597
Occupation, forest, intensive, normal	m^2a	x	x	6170.40791	x	x	6170.4078
Oil, crude, 42 MJ per kg, in ground	g	x	17.576184	x	x	x	17.576184
Oil, crude, in ground	oz	198.97241	204.36755	273.040252	109.57151	200.7997	986.75143
Uranium oxide, 332 GJ per kg, in ore	g	1.4769607	0.8267759	0.00981362	0.00393822	0.00721715	2.3247055
Uranium, 2291 GJ per kg, in ground	µg	x	59.162472	x	x	x	59.162472
Water, process and cooling, surface	dm 3	x	611.64361	x	x	x	611.64361
Water, well, in ground	dm 3	x	129.95131	x	x	x	129.95131
Wood and wood waste, 20.9 MJ per kg, ovendry basis	kg	x	1.2399468	x	x	x	1.2399468
OUTPUTS							
Air Emissions							
2-Chloroacetophenone	ng	89.363988	50.030022	0.60968479	0.24466753	0.44837536	140.69674
5-methyl Chrysene	ng	577.52077	323.33523	3.97616748	1.5956426	2.9241594	909.35197
Acenaphthene	µg	13.38764	7.4953075	0.09217246	0.03698896	0.06778562	21.079895
Acenaphthylene	µg	6.5627571	3.6742758	0.04518386	0.01813236	0.03322919	10.333578
Acetaldehyde	g	6.0384618	0.10493487	0.1047892	2.70E-05	4.94E-05	6.2482623
Acetic acid	g	98.548079	x	x	x	x	98.548079
Acetophenone	ng	191.49426	107.20719	1.30646741	0.52428755	0.96080433	301.49301
Acrolein	g	12.667284	0.24517688	0.01269007	2.43E-05	4.45E-05	12.925219
Aldehydes, unspecified	g	0.2547764	0.24969792	0.31459033	0.12624563	0.23135652	1.1766668
Ammonia	mg	249.2905	193.09177	158.116491	63.452412	116.28228	780.23345
Ammonium chloride	mg	78.391485	43.882137	0.52086967	0.20902587	0.3830588	123.38658
Anthracene	µg	5.5127299	3.0863995	0.03795454	0.01523122	0.02791259	8.6802278
Antimony	mg	5.6919615	0.72693182	0.00325324	0.00130553	0.0023925	6.4258446

Arsenic	mg	25.647431	7.530936	0.1057842	0.04245138	0.07779598	33.404399
Benzene	g	2.8596594	0.33429604	0.12773196	0.00013788	0.00025267	3.322078
Benzene, chloro-	ng	280.85825	157.23721	1.91615216	0.76895508	1.4091797	442.18975
Benzene, ethyl-	µg	1.2959955	23.302612	0.0081872	0.00328554	0.00602104	24.616102
Benzo(a)anthracene	µg	2.1000544	1.1757527	0.01445865	0.00580228	0.0106332	3.3067012
Benzo(a)pyrene	µg	0.99754292	0.55849208	0.00686797	0.00275613	0.00505085	1.57071
Benzo(b,j,k)fluoranthene	µg	2.8876038	1.6166762	0.01988084	0.00797821	0.0146208	4.5467599
Benzo(ghi)perylene	µg	0.70878356	0.39682504	0.0048799	0.00195831	0.00358878	1.1160356
Benzyl chloride	µg	8.9363988	5.0030022	0.06096848	0.02446675	0.04483754	14.069674
Beryllium	mg	1.3101705	0.39816281	0.00516832	0.00207406	0.0038009	1.7193766
Biphenyl	µg	44.627027	24.985232	0.30725217	0.12330081	0.22595988	70.268772
Bromoform	ng	497.88508	278.7387	3.39681523	1.3631476	2.4980913	783.88183
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	g	1.6751702	1.0797123	0.10484531	0.0420746	0.07710551	2.9789079
Butadiene	mg	2.0605634	2.8716339	5.34213319	0.00137427	0.00251848	10.278223
Cadmium	mg	4.2786736	1.1381582	0.02607281	0.01046306	0.01917451	5.4725422
Carbon dioxide, biogenic	lb	289.9618	25.470252	0.04037079	0.01620086	0.02968955	315.51831
Carbon dioxide, fossil	kg	146.31689	90.872294	24.9977049	10.816707	19.822594	292.82619
Carbon disulfide	µg	1.6596169	0.92912898	0.01132272	0.00454383	0.00832697	2.6129394
Carbon monoxide	g	934.8004	35.507683	0.00471266	0.0018912	0.00346579	970.31815
Carbon monoxide, fossil	g	150.81529	205.06467	233.70402	56.579904	103.68779	749.85167
Chloride	µg	2.0615951	1.1541634	0.01403354	0.00563168	0.01032057	3.2457443
Chlorine	mg	521.94434	46.238422	x	x	x	568.18276
Chloroform	µg	0.75321076	0.42168162	0.00513877	0.0020622	0.00377916	1.1858725
Chromium	mg	21.061687	5.2785495	0.07580558	0.03042091	0.05574906	26.502212
Chromium VI	mg	2.0737954	1.1610511	0.01427786	0.00572973	0.01050025	3.2653543
Chrysene	µg	2.6251261	1.4697233	0.0180737	0.00725301	0.01329179	4.1334679
Cobalt	mg	8.2802603	2.66E+00	0.15301879	0.0614067	0.11253332	11.270684
Copper	µg	49.391865	41.277562	1.34635172	0.54029319	0.99013612	93.546207
Cumene	ng	67.661305	37.879874	0.46161849	0.18524827	0.3394842	106.52753
Cyanide	µg	31.91571	17.867865	0.21774457	0.08738126	0.16013406	50.248835
Dinitrogen monoxide	g	0.32510181	0.2154795	0.02749	0.24925301	0.45677866	1.274103
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	mg	1.1033598	0.09756306	4.8605E-07	1.95E-07	3.57E-07	1.2009239
Ethane, 1,1,1-trichloro-, HCFC-140	µg	0.78448654	0.68645197	0.72788391	0.29210103	0.53530154	3.026225
Ethane, 1,2-dibromo-	ng	15.319541	8.5765752	0.10451739	0.041943	0.07686435	24.119441
Ethane, 1,2-dichloro-	ng	510.65136	285.88584	3.48391307	1.3981001	2.5621449	803.98136
Ethane, chloro-	ng	536.18393	300.18013	3.65810877	1.4680052	2.6902521	844.18043
Ethene, tetrachloro-	mg	1.1515225	0.64654803	0.00947472	0.00380222	0.00696792	1.8183154
Fluoranthene	µg	18.638357	10.435014	0.12832302	0.05149624	0.09437152	29.347562
Fluorene	µg	23.887946	13.37409	0.16446609	0.06600052	0.12095192	37.613455

Fluoride	mg	2.3344596	1.3067883	0.01551138	0.00622474	0.0114074	3.6743914
Formaldehyde	g	7.0782082	0.35657693	0.16250205	0.00055433	0.00101586	7.5988574
Furan	ng	123.99828	69.411622	0.82285578	0.3302134	0.6051459	195.16812
Hexane	µg	0.85534103	0.47885878	0.00583555	0.00234182	0.00429159	1.3466688
Hydrazine, methyl-	µg	2.1702683	1.2150148	0.01480663	0.00594193	0.01088912	3.4169208
Hydrocarbons, unspecified	mg	452.44635	253.27129	3.00626511	1.2064192	2.2108723	712.1412
Hydrogen chloride	g	44.245262	18.872841	0.23357651	0.09373464	0.17177721	63.617191
Hydrogen fluoride	g	3.9370761	2.2042418	0.02710648	0.01087788	0.01993469	6.1992369
Hydrogen sulfide	ng	66.637677	37.306435	0.45361122	0.18203494	0.33359548	104.91335
Indeno(1,2,3-cd)pyrene	µg	1.6013579	0.8965486	0.01102517	0.00442442	0.00810815	2.5214642
Isophorone	µg	7.4044447	4.1453447	0.05051674	0.02027245	0.0371511	11.65773
Isoprene	g	67.572416	37.829739	0.45997411	0.18458838	0.33827489	106.38499
Kerosene	mg	37.543825	21.016355	0.24945872	0.1001082	0.18345733	59.093204
Lead	mg	43.30972	9.34E+00	0.11597402	0.04654057	0.0852898	52.896965
Magnesium	mg	288.76038	161.66762	1.98808371	0.79782132	1.4620797	454.67599
Manganese	g	1.0707265	0.10131719	0.00015938	6.40E-05	0.00011721	1.1723842
Mercaptans, unspecified	mg	2.6649881	1.4918052	0.01768775	0.00709813	0.01300796	4.1945872
Mercury	mg	4.5844999	1.4868411	0.02002753	0.00803708	0.01472868	6.1141342
Metals, unspecified	g	28.258404	2.5037683	5.2039E-11	2.09E-11	3.83E-11	30.762173
Methane	g	292.61746	171.64754	32.3938307	12.999698	23.823122	533.48165
Methane, bromo-, Halon 1001	µg	2.0426054	1.14E+00	0.01393565	0.0055924	0.01024858	3.2159254
Methane, dichloro-, HCC-30	mg	200.56071	22.103994	0.16727991	0.06712971	0.12302126	223.02213
Methane, dichlorodifluoro-, CFC-12	µg	0.65461164	0.67236143	0.89829202	0.36048608	0.66062333	3.2463745
Methane, fossil	g	14.413162	9.7417674	2.41843759	0.64466794	1.1814123	28.399447
Methane, monochloro-, R-40	µg	6.7661305	3.7879874	0.04616185	0.01852483	0.03394842	10.652753
Methane, tetrachloro-, CFC-10	mg	29.731072	2.6339014	8.9829E-05	3.60E-05	6.61E-05	32.365166
Methyl ethyl ketone	µg	4.9788508	2.787387	0.03396815	0.01363148	0.02498091	7.8388183
Methyl methacrylate	ng	255.32568	142.94292	1.74195655	0.69905007	1.2810724	401.99068
Naphthalene	mg	64.74647	6.0621888	0.03161955	0.01268898	0.0232537	70.876221
Nickel	mg	48.37474	17.545734	1.95148271	0.78313325	1.4351625	70.090252
Nitrogen oxides	oz	30.325876	16.438557	16.0545048	2.5915964	4.7493347	70.159869
NMVOC, non-methane volatile organic compounds, unspecified origin	g	16.791975	14.57561	15.2355127	6.1138321	11.20415	63.92108
Organic acids	µg	288.06836	161.25546	1.91406085	0.76811583	1.4076417	453.41364
Organic substances, unspecified	mg	162.77428	91.132853	1.12288695	0.4506164	0.82579529	256.30644
Ozone	g	4.5413861	x	x	x	x	4.5413861
PAH, polycyclic aromatic hydrocarbons	mg	8.8534149	12.338542	22.9530024	0.00590493	0.01082132	44.161685
Particulates	kg	1.6012928	x	x	x	x	1.6012928
Particulates, < 10 um	kg	1.497295	x	x	x	x	1.497295
Particulates, > 2.5 um, and <	g	342.54277	40.208615	13.9185948	1.3200066	2.4190314	400.40902

10um							
Particulates, unspecified	oz	3.1350071	51.514461	0.08457512	0.03394014	0.06219837	54.830182
Phenanthrene	µg	70.878356	39.682504	0.48798998	0.1958312	0.35887837	111.60356
Phenol	ng	204.26054	114.35434	1.39356524	0.55924006	1.024858	321.59254
Phenols, unspecified	mg	35.130944	3.8743824	0.08944203	0.03589324	0.0657776	39.19644
Phthalate, dioctyl-	µg	0.93193873	0.52174166	0.00635814	0.00255153	0.00467591	1.467266
Propanal	µg	4.8511879	2.7159155	0.03309717	0.01328195	0.02434038	7.6378229
Propene	mg	135.96402	189.46185	352.495041	0.09068118	0.16618147	678.17777
Propylene oxide	µg	0.08696924	20.509416	x	x	x	20.596385
Pyrene	µg	8.662815	4.8500304	0.05964255	0.02393466	0.04386242	13.640285
Radioactive species, unspecified	Bq	1484860.1	831348.91	10242.8169	4110.4595	7532.7886	2338095
Radionuclides (Including Radon)	g	2.0994813	1.1752517	0.01394994	0.00559813	0.01025908	3.3045401
Selenium	mg	36.256067	19.466794	0.25373078	0.10182258	0.18659909	56.265014
Styrene	ng	319.1571	178.67865	2.17744566	0.87381259	1.6013406	502.48835
Sulfur dioxide	oz	32.013189	18.275919	0.44972712	0.18047624	0.33073903	51.25005
Sulfur oxides	g	58.28546	33.421238	25.2933399	10.302508	18.880277	146.18282
Sulfuric acid, dimethyl ester	ng	612.78163	343.06301	4.18069575	1.6777202	3.0745739	964.77763
t-Butyl methyl ether	ng	446.81994	250.15011	3.04842394	1.2233376	2.2418768	703.48369
Tar	µg	2.3187283	1.2981168	0.01578388	0.0063341	0.01160781	3.6505708
TOC, Total Organic Carbon	g	2.7022182	0.23932123	x	x	x	2.9415394
Toluene	mg	21.557486	30.128546	55.8801681	0.01438376	0.02635955	107.60694
Toluene, 2,4-dinitro-	ng	3.5745595	2.0012009	0.02438739	0.0097867	0.01793501	5.6278695
Vinyl acetate	ng	97.023759	54.31831	0.66194349	0.26563903	0.48680753	152.75646
VOC, volatile organic compounds	g	614.70681	12.268585	12.1910774	3.535218	6.4786066	649.18029
Xylene	g	1.8315746	0.02097471	0.03893894	1.00E-05	1.84E-05	1.8915166
Zinc	µg	32.92791	27.518374	0.89756782	0.36019546	0.66009074	62.364138
Water Emissions							
2-Hexanone	µg	271.58517	225.13711	188.469575	75.633155	138.60459	899.4296
4-Methyl-2-pentanone	µg	174.79781	144.90271	121.302327	48.678826	89.208349	578.89002
Acetone	mg	0.4159317	0.34479545	0.28863632	0.11583024	0.21226938	1.3774631
Acids, unspecified	µg	43.304281	24.243467	0.29477781	0.11829482	0.21678596	68.177607
Aluminium	g	2.8105577	2.4471413	2.4960757	1.0016794	1.835668	10.591122
Ammonia	g	0.6859415	0.58501527	0.54109511	0.21714237	0.39793302	2.4271273
Ammonia, as N	µg	21.747848	12.175314	0.14804039	0.05940886	0.1088721	34.239483
Ammonium, ion	mg	16.760588	9.3822741	0.11136518	0.04469103	0.08190036	26.380818
Antimony	mg	1.3655872	1.3099878	1.55684081	0.62476281	1.1449343	6.0021129
Arsenic, ion	mg	10.820578	9.053126	7.91344212	3.1756776	5.8197162	36.78254
Barium	g	30.748015	29.235696	34.1628352	13.709603	25.124086	132.98023
Benzene	mg	69.776306	57.84249	48.4211253	19.431479	35.609941	231.08134
Benzene, 1-methyl-4-(1-methylethyl)-	µg	4.1564109	3.4455419	2.88433442	1.1574882	2.1212018	13.764977
Benzene, ethyl-	mg	3.9250833	3.2537781	2.72380494	1.0930675	2.0031449	12.998879

Benzene, pentamethyl-	µg	3.1173194	2.5841744	2.16328844	0.86813126	1.590929	10.323843
Benzenes, alkylated, unspecified	mg	1.1973867	1.148834	1.3657626	0.54808281	1.0044113	5.2644774
Benzoic acid	mg	42.193965	34.977487	29.2802145	11.750199	21.533301	139.73517
Beryllium	mg	0.52696187	0.45869053	0.44049898	0.17677298	0.32395246	1.9268768
Biphenyl	µg	77.526198	74.382382	88.4271709	35.485971	65.03125	340.85297
BOD5, Biological Oxygen Demand	oz	45.577558	4.2329588	0.18625766	0.07474551	0.1369779	50.208497
Boron	mg	130.54625	108.21921	90.5931299	36.355174	66.624143	432.3379
Bromide	g	8.9125897	7.3879973	6.18393071	2.4816217	4.5477961	29.513936
Cadmium, ion	mg	1.7690999	1.4317156	1.16864946	0.46898098	0.85945003	5.6978959
Calcium, ion	g	133.66306	110.79264	92.7231508	37.209955	68.190606	442.57941
Chloride	oz	52.998726	43.93197	36.771023	14.756273	27.042203	175.50019
Chromium	mg	47.970821	49.271549	65.8280461	26.416905	48.411366	237.89869
Chromium VI	mg	0.20184376	0.20731675	0.27698047	0.11115272	0.20369741	1.0009911
Chromium, ion	mg	14.018863	10.225335	4.94985277	1.9863842	3.6402286	34.820663
Cobalt	mg	0.92149961	0.76389539	0.63947115	0.25662084	0.47028088	3.0517679
COD, Chemical Oxygen Demand	g	13.223036	11.209345	10.0251951	4.0231275	7.3727449	45.853448
Copper, ion	mg	24.365472	16.601647	8.22008534	3.298734	6.0452282	58.531167
Cyanide	µg	3.1374038	2.5643409	2.08407087	0.83634112	1.5326707	10.154827
Decane	mg	1.2124361	1.0050767	0.84137822	0.33764648	0.6187677	4.0153052
Detergent, oil	mg	38.169015	30.989598	24.2574431	9.7345522	17.839447	120.99005
Dibenzofuran	µg	7.9088212	6.5561731	5.4882923	2.2024609	4.0362086	26.191956
Dibenzothiophene	µg	6.6471007	5.5414656	4.71960325	1.8939847	3.4708981	22.273052
DOC, Dissolved Organic Carbon	ng	132.97228	74.443198	0.9051594	0.36324197	0.66567375	209.34955
Docosane	µg	44.508485	36.896143	30.8863255	12.394734	22.71447	147.40016
Dodecane	mg	2.3004075	1.9069697	1.59636329	0.64062325	1.174	7.6183638
Eicosane	mg	0.63336405	0.52503947	0.43951977	0.17638002	0.32323233	2.0975356
Fluorene, 1-methyl-	µg	4.7337065	3.9241083	3.28496613	1.3182624	2.415835	15.676878
Fluorenes, alkylated, unspecified	µg	69.391798	66.57787	79.1490745	31.762656	58.207938	305.08934
Fluoride	mg	272.62793	152.61219	1.8114708	0.72694626	1.3321947	429.11073
Fluorine	µg	35.642596	33.73036	39.056086	15.673272	28.722688	152.825
Hexadecane	mg	2.5108831	2.0814523	1.74243792	0.69924325	1.2814265	8.315443
Hexanoic acid	mg	8.7379232	7.2434792	6.06366354	2.4333583	4.459349	28.937773
Hydrocarbons, unspecified	ng	166.38045	93.146424	1.13257306	0.45450346	0.83291867	261.94686
Iron	g	6.2376732	5.2617339	4.97418378	1.9961482	3.6581221	22.127861
Lead	mg	20.796706	17.734805	16.6312341	6.674142	12.230969	74.067855
Lead-210/kg	pg	4.3217224	3.5825845	2.99906645	1.2035304	2.2055782	14.312482
Lithium, ion	g	23.147075	14.927424	1.47691589	0.59268881	1.0861558	41.23026
m-Xylene	mg	1.2602147	1.0446766	0.87450965	0.35094218	0.64313327	4.1734765
Magnesium	g	26.128605	21.65826	18.1264862	7.2741891	13.330609	86.518149
Manganese	mg	517.87872	301.13174	32.0687615	12.869247	23.584059	887.53253
Mercury	µg	45.628041	35.10499	27.4367765	11.010424	20.177598	139.35783

Metallic ions, unspecified	µg	2.0314155	1.1372676	0.01382811	0.00554924	0.01016949	3.1982299
Methane, monochloro-, R-40	µg	1.6741709	1.3878384	1.16178861	0.46622771	0.85440442	5.54443
Methyl ethyl ketone	µg	3.3482174	2.775575	2.3234955	0.93242264	1.7087488	11.088459
Molybdenum	mg	0.95615181	0.79262215	0.66352177	0.2662724	0.48796824	3.1665364
n-Hexacosane	µg	27.76734	23.018338	19.2692134	7.7327675	14.170995	91.958655
Naphthalene	mg	0.75660802	0.6274558	0.52590301	0.21104576	0.38676042	2.507773
Naphthalene, 2-methyl-	mg	0.65882286	0.54614452	0.45718842	0.18347048	0.33622623	2.1818525
Naphthalenes, alkylated, unspecified	µg	19.620988	18.825346	22.3799728	8.9811203	16.458715	86.266142
Nickel	mg	9.2823551	8.0916605	7.80004377	3.1301705	5.7363205	34.04055
Nitrate	ng	14.576832	8.1606933	0.09922637	0.03981971	0.07297321	22.949545
Nitrate compounds	ng	586.87605	328.55667	3.99494067	1.6031764	2.9379656	923.96881
Nitric acid	mg	1.3163876	0.7369664	0.00896082	0.00359599	0.00658998	2.0725008
Nitrogen, total	mg	41.7238	23.356229	0.27723243	0.11125384	0.20388272	65.672398
o-Cresol	mg	1.1965439	0.99189866	0.83033654	0.33321544	0.61064741	3.962642
Octadecane	mg	0.62031575	0.51422314	0.43046602	0.17274673	0.31657401	2.0543257
Oils, unspecified	g	0.98728146	0.80560592	0.66613804	0.26732231	0.48989229	3.21624
p-Cresol	mg	1.2909951	1.0701914	0.89586529	0.35951224	0.65883867	4.2754027
Phenanthrene	µg	8.4802782	7.6543218	8.02244279	3.2194197	5.8998776	33.27634
Phenanthrenes, alkylated, unspecified	µg	8.1356633	7.8057583	9.27965309	3.7239403	6.8244572	35.769472
Phenol	mg	8.9331392	9.1751687	12.2579539	4.9191374	9.0147639	44.300163
Phenol, 2,4-dimethyl-	mg	1.1650647	0.96580401	0.8084939	0.32444995	0.59458387	3.8583965
Phenols, unspecified	mg	10.892533	7.5006916	2.32501941	0.93303418	1.7098695	23.361147
Radioactive species, Nuclides, unspecified	Bq	2434.476	1362.7757	16.1757971	6.4913744	11.89603	3831.8149
Radium-226/kg	ng	1.5035332	1.2463918	1.04339877	0.41871767	0.76733798	4.9793794
Radium-228/kg	pg	7.6909841	6.3755863	5.33710284	2.1417883	3.9250206	25.470482
Selenium	mg	6.1327085	3.5388435	0.3409254	0.13681393	0.25072389	10.400015
Silver	mg	87.260701	72.357532	60.6262612	24.32942	44.585861	289.15977
Sodium, ion	oz	14.946435	12.388957	10.3683583	4.1608395	7.6251144	49.489704
Solids, inorganic	µg	3.3468779	1.873716	0.02278263	0.00914271	0.01675484	5.2692742
Solved solids	oz	65.374373	54.189102	45.3527277	18.200125	33.353375	216.4697
Strontium	g	2.2674898	1.8796889	1.57354412	0.63146588	1.1572183	7.5094071
Sulfate	g	37.01735	21.537079	2.32469759	0.93290501	1.7096328	63.521664
Sulfide	mg	1.0367627	1.064748	1.42232979	0.57078331	1.046012	5.1406358
Sulfur	mg	110.19955	91.352171	76.4727827	30.688655	56.239735	364.9529
Suspended solids, unspecified	g	75.142004	69.038683	76.7065478	30.782466	56.411651	308.08135
Tar	ng	33.168897	18.569274	0.22578494	0.09060787	0.16604712	52.220612
Tetradecane	mg	1.0081776	0.83574939	0.69962286	0.28075982	0.51451775	3.3388275
Thallium	mg	0.28791393	0.27613755	0.32805182	0.13164774	0.24125638	1.2650074
Tin	mg	6.880066	6.1592065	6.3348594	2.5421896	4.6587923	26.575114
Titanium, ion	mg	20.976481	20.120692	23.9083301	9.5944529	17.582702	92.182659

Toluene	mg	65.923107	54.648316	45.7472539	18.358449	33.643517	218.32064
Vanadium	mg	1.1294592	0.93628803	0.78378522	0.31453432	0.57641257	3.7404794
Xylene	mg	34.807736	28.975038	24.5671116	9.8588229	18.067184	116.27589
Yttrium	µg	280.3025	232.3635	194.518876	78.060749	143.05338	928.299
Zinc	mg	78.225761	64.047347	57.6781582	23.146341	42.417762	265.51537

Appendix C. Cradle-to-gate LCI for producing one short ton of premium grade wood pellets in Wisconsin in 2009 using DRY CO-PRODUCT feedstock.

Cradle-To-Gate Life Cycle Inventory for Producing One Ton of Premium Wood Pellets from Dry Co-Product		Producing One Ton Wood Pellets at Pellet Mill	Producing Dry Co-Product Feedstock at Sawmill	Growth and Harvest of Timber	Diesel Transport from Sawmill to Pelletmill	Diesel Transport from Forest to Sawmill	Total
INPUTS							
Coal, 26.4 MJ per kg, in ground	lb	107.61372	139.82942	0.64272842	0.24255746	0.54537763	248.87381
Gas, natural, 46.8 MJ per kg, in ground	g	x	136.27462	x	x	x	136.27462
Gas, natural, in ground	cu ft	191.519151	1032.81043	10.6199575	4.00783572	9.01140687	1247.96878
Oil, crude, 42 MJ per kg, in ground	g	x	614.96081	x	x	x	614.96081
Oil, crude, in ground	lb	6.5235201	29.693682	12.0586522	4.5507806	10.23219	63.058825
Uranium oxide, 332 GJ per kg, in ore	g	1.1952193	1.5521227	0.0069346	0.00261703	0.00588425	2.7627779
Uranium, 2291 GJ per kg, in ground	mg	x	2.0699943	x	x	x	2.0699943
Wood and wood waste, 20.9 MJ per kg, ovendry basis	kg	x	43.383631	x	x	x	43.383631
Carbon dioxide, in air	kg	2.1768551	82.350023	1602.38414	0.00488329	0.01097981	1686.9269
Occupation, forest, intensive, normal	m^2a	x	x	4971.93921	x	x	4971.9392
Water, well, in ground	cm3	x	445.75261	x	x	x	445.75261
Limestone, in ground	kg	x	5.0024862	x	x	x	5.0024862
OUPUTS							
Air Emissions							
2-Chloroacetophenone	ng	72.313819	93.938566	0.43082165	0.16258656	0.36556729	167.21136
5-methyl Chrysene	µg	0.4673254	0.60714517	0.00280968	0.00106034	0.00238411	1.0807247
Acenaphthene	µg	10.833176	14.07437	0.06513184	0.02457992	0.05526665	25.052525
Acenaphthylene	µg	5.310533	6.8993991	0.03192828	0.01204932	0.02709227	12.281002
Acetaldehyde	g	5.460827	2.2931556	0.07405106	1.79E-05	4.03E-05	7.828092
Acetic acid	g	98.552309	x	x	x	x	98.552309
Acetophenone	ng	154.95818	201.29693	0.92318923	0.34839977	0.78335849	358.31006
Acrolein	g	4.5490572	10.597331	0.00896765	1.61E-05	3.63E-05	15.155409
Aldehydes, unspecified	g	0.14095133	0.57405998	0.222299	0.08389279	0.18862852	1.2098316
Ammonia	mg	169.12182	415.15776	111.729874	42.165421	94.806724	832.9816
Ammonium chloride	mg	63.437719	82.380799	0.3680622	0.13890195	0.31231371	146.6378
Anthracene	µg	4.460859	5.7955099	0.02681982	0.01012146	0.02275756	10.316068
Antimony	mg	0.382358	21.387261	0.00229883	0.00086755	0.00195064	21.774736
Arsenic	mg	8.9858628	70.129916	0.0747503	0.02820981	0.06342826	79.282168
Benzene	g	0.0420902	11.264068	0.09026395	9.16E-05	0.000206	11.39672
Benzene, chloro-	ng	227.272	295.23549	1.35401087	0.51098633	1.1489258	525.52142

Benzene, ethyl-	µg	1.0443602	28.167157	0.00578532	0.00218331	0.00490905	29.224395
Benzo(a)anthracene	µg	1.699348	2.2077784	0.01021692	0.00385573	0.00866941	3.9298685
Benzo(a)pyrene	µg	0.80720411	1.0487127	0.00485312	0.0018315	0.00411804	1.8667195
Benzo(b,j,k)fluoranthene	µg	2.336627	3.0357259	0.0140484	0.00530169	0.01192056	5.4036235
Benzo(ghi)perylene	µg	0.57354225	0.7451412	0.00344828	0.00130134	0.00292599	1.3263591
Benzyl chloride	µg	7.2313819	9.3938566	0.04308216	0.01625866	0.03655673	16.721136
Beryllium	mg	0.47185292	3.6559016	0.00365209	0.00137825	0.00309893	4.1358838
Biphenyl	µg	36.11185	46.916207	0.21711364	0.0819359	0.18422855	83.511335
Bromoform	ng	402.89128	523.37201	2.40029204	0.9058394	2.0367321	931.60616
BTEX (Benzene, Toluene, Ethylbenzene, and Xylene), unspecified ratio	g	1.3360743	7.2050835	0.07408686	0.02795943	0.0628653	8.7060693
Butadiene	mg	0.55689449	5.0111219	3.7751083	0.00091323	0.00205336	9.3460912
Cadmium	mg	1.267127	13.008423	0.01842383	0.00695292	0.01563327	14.31656
Carbon dioxide, biogenic	lb	4.7991436	978.95985	0.02852721	0.01076581	0.02420634	983.8225
Carbon dioxide, fossil	kg	113.38876	218.71741	17.6509506	7.1879226	16.161665	373.10671
Carbon disulfide	µg	1.3429709	1.7445734	0.00800097	0.00301946	0.00678911	3.1053539
Carbon monoxide	oz	18.990269	56.302402	0.00011747	4.43E-05	9.97E-05	75.292932
Carbon monoxide, fossil	g	76.82852	427.32484	170.066457	37.5985	84.538241	796.35656
Chloride	µg	1.6682605	2.1670755	0.00991652	0.00374237	0.00841452	3.8574094
Chlorine	g	x	2.0890505	x	x	x	2.0890505
Chloroform	µg	0.60950219	0.79176792	0.00363121	0.00137037	0.00308121	1.4093529
Chromium	mg	5.8103534	63.717264	0.05356651	0.02021531	0.04545306	69.646852
Chromium VI	mg	1.6780994	2.1801724	0.01008917	0.00380752	0.00856101	3.8807295
Chrysene	µg	2.124232	2.7597841	0.01277142	0.00481977	0.010837	4.9124442
Cobalt	mg	3.199087	21.548215	0.10812769	0.040806	0.09175014	24.987986
Copper	µg	39.757751	309.89739	0.95137269	0.35903584	0.80727314	351.77283
Cumene	ng	54.751892	71.124914	0.32619353	0.12310125	0.27678667	126.60289
Cyanide	µg	25.826364	33.549488	0.15386487	0.05806663	0.13055975	59.718343
Dinitrogen monoxide	g	0.25943942	0.58002759	0.02186993	0.1656337	0.37241864	1.3993893
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	mg	1.92E-05	4.4073091	3.4346E-07	1.30E-07	2.91E-07	4.4073291
Ethane, 1,1,1-trichloro-, HCFC-140	µg	0.4841965	1.5319067	0.5143447	0.19410709	0.43643954	3.1609945
Ethane, 1,2-dibromo-	ng	12.396655	16.103754	0.07385514	0.02787198	0.06266868	28.664805
Ethane, 1,2-dichloro-	ng	413.22183	536.79181	2.46183798	0.92906605	2.088956	955.49349
Ethane, chloro-	µg	0.43388292	0.5636314	0.00258493	0.00097552	0.0021934	1.0032682
Ethene, tetrachloro-	mg	0.93148081	1.2358742	0.00669512	0.00252665	0.00568105	2.1822578
Fluoranthene	µg	15.082016	19.594427	0.09067691	0.0342203	0.07694254	34.878282
Fluorene	µg	19.329944	25.113299	0.1162167	0.04385869	0.09861395	44.701932
Fluoride	mg	1.8891438	2.4532596	0.01096081	0.00413647	0.00930063	4.3668013
Formaldehyde	g	4.1215877	11.836427	0.11483473	0.00036836	0.00082824	16.074046
Furan	ng	100.34489	130.30674	0.58145468	0.21943354	0.49338472	231.9459
Hexane	µg	0.69214656	0.89912628	0.00412358	0.00155619	0.003499	1.6004516

Hydrazine, methyl-	µg	1.7561928	2.2813652	0.01046281	0.00394853	0.00887806	4.0608473
Hydrocarbons, unspecified	mg	366.13881	475.47118	2.12431749	0.80169016	1.802558	846.33856
Hydrogen chloride	g	25.641856	83.793992	0.1650522	0.06228858	0.14005259	109.80324
Hydrogen fluoride	g	3.1858519	4.1390319	0.01915425	0.00722857	0.01625306	7.3675196
Hydrogen sulfide	ng	53.923779	70.047157	0.32053536	0.12096593	0.27198551	124.68442
Indeno(1,2,3-cd)pyrene	µg	1.2958066	1.6835009	0.00779072	0.00294012	0.0066107	2.996649
Isophorone	µg	5.9917165	7.7834812	0.03569665	0.01347146	0.03028986	13.854656
Isoprene	g	54.680179	71.029721	0.32503156	0.12266274	0.2758007	126.4334
Kerosene	mg	30.382058	39.454416	0.17627506	0.06652394	0.14957557	70.228849
Lead	mg	9.3763854	139.71567	0.08195074	0.03092716	0.06953808	149.27447
Magnesium	mg	233.6627	303.57259	1.40483986	0.53016854	1.192056	540.36235
Manganese	g	0.0110108	4.2457699	0.00011262	4.25E-05	9.56E-05	4.2570314
Mercaptans, unspecified	mg	2.1566257	2.8005752	0.0124987	0.00471685	0.01060559	4.985022
Mercury	mg	1.8376424	11.864861	0.01415206	0.0053408	0.01200852	13.734005
Metals, unspecified	g	6.19E-09	113.12017	3.6772E-11	1.39E-11	3.12E-11	113.12017
Methane	g	219.2038	569.82305	22.8904569	8.6385647	19.423357	839.97923
Methane, bromo-, Halon 1001	µg	1.6528873	2.1471672	0.00984735	0.00371626	0.00835582	3.821974
Methane, dichloro-, HCC-30	mg	7.2290688	777.78648	0.11820503	0.04460906	0.10030112	785.27866
Methane, dichlorodifluoro-, CFC-12	µg	0.34339417	1.5630576	0.63476019	0.23955035	0.53861632	3.3193786
Methane, fossil	g	11.200984	47.400291	1.74106526	0.42839499	0.96322352	61.733959
Methane, monochloro-, R-40	µg	5.4751892	7.1124914	0.03261935	0.01231013	0.02767867	12.660289
Methane, tetrachloro-, CFC-10	mg	3.43E-05	118.9967	6.3476E-05	2.40E-05	5.39E-05	118.99688
Methyl ethyl ketone	µg	4.0289128	5.2337201	0.02400292	0.00905839	0.02036732	9.3160616
Methyl methacrylate	ng	206.61091	268.3959	1.23091899	0.46453303	1.044478	477.74675
Naphthalene	mg	0.52812478	257.43418	0.02234333	0.00843208	0.0189591	258.01204
Nickel	mg	21.133202	118.02486	1.37897643	0.52040801	1.1701099	142.22756
Nitrogen oxides	oz	17.844119	53.390704	11.3250987	1.7221687	3.8722053	88.154296
NMVOC, non-methane volatile organic compounds, unspecified origin	g	10.436143	32.457348	10.7658725	4.0627661	9.1349151	66.857045
Organic acids	µg	233.11716	302.72806	1.35253307	0.51042863	1.1476718	538.85585
Organic substances, unspecified	mg	131.71525	171.12765	0.79346573	0.29944379	0.67328355	304.60909
Ozone	g	4.541581	x	x	x	x	4.541581
PAH, polycyclic aromatic hydrocarbons	mg	2.3927556	21.531131	16.2201285	0.00392395	0.00882279	40.156762
Particulates	kg	1.6013615	x	x	x	x	1.6013615
Particulates, < 10 um	kg	1.4973593	x	x	x	x	1.4973593
Particulates, > 2.5 um, and < 10um	oz	0.24531108	47.441705	0.3452192	0.03094131	0.0695699	48.132746
Particulates, unspecified	oz	2.5236931	62.341517	0.05976333	0.02255391	0.05071128	64.998239
Phenanthrene	µg	57.354225	74.51412	0.34482843	0.13013382	0.29259903	132.63591
Phenol	ng	165.28873	214.71672	0.98473518	0.37162642	0.83558239	382.1974
Phenols, unspecified	mg	1.1452571	137.50191	0.06320243	0.02385179	0.05362948	138.78785

Phthalate, dioctyl-	µg	0.75412983	0.97964505	0.00449285	0.00169555	0.00381234	1.7437756
Propanal	µg	3.9256073	5.0995222	0.02338746	0.00882613	0.01984508	9.0771882
Propene	mg	36.746046	330.63003	249.09657	0.0602595	0.13549029	616.66839
Propylene oxide	µg	0.06641893	24.383609	x	x	x	24.450028
Pyrene	µg	7.0098837	9.1071812	0.04214522	0.01590507	0.0357617	16.210877
Radioactive species, unspecified	Bq	1201533.3	1561400.3	7237.88292	2731.4841	6141.5979	2779044.6
Radionuclides (Including Radon)	g	1.6989894	2.2063231	0.00985744	0.00372007	0.00836439	3.9272545
Selenium	mg	27.837672	44.244399	0.17929381	0.06766318	0.1521371	72.481165
Styrene	ng	258.26364	335.49488	1.53864869	0.58066628	1.3055975	597.18343
Sulfur dioxide	oz	25.857002	47.238355	0.31779073	0.11993014	0.2696566	73.802734
Sulfur oxides	g	28.585091	135.34713	17.8716802	6.8462266	15.393379	204.04351
Sulfuric acid, dimethyl ester	µg	0.49586619	0.64415017	0.00295421	0.00111488	0.00250675	1.1465922
t-Butyl methyl ether	ng	361.5691	469.69283	2.15410818	0.8129328	1.8278365	836.05681
Tar	µg	1.8763348	2.4373647	0.01115337	0.00420914	0.00946402	4.338526
TOC, Total Organic Carbon	g	x	10.812526	x	x	x	10.812526
Toluene	mg	5.8280337	52.526446	39.4886618	0.0095583	0.02149134	97.874191
Toluene, 2,4-dinitro-	ng	2.8925528	3.7575427	0.01723287	0.00650346	0.01462269	6.6884544
Vinyl acetate	ng	78.512147	101.99044	0.46774921	0.17652255	0.39690163	181.54376
VOC, volatile organic compounds	oz	21.524466	70.775924	0.30617151	0.08286646	0.18632087	92.875748
Xylene	g	1.8206922	0.03657785	0.02751686	6.66E-06	1.50E-05	1.8848085
Zinc	µg	26.505167	206.59826	0.63424846	0.23935723	0.53818209	234.51522
Water Emissions							
2-Hexanone	mg	0.1808665	0.91760642	0.13317828	0.05025977	0.11300645	1.3949174
4-Methyl-2-pentanone	µg	116.40952	590.59123	85.7158782	32.348073	72.732933	897.79763
Acetone	mg	0.27699725	1.405317	0.20395912	0.07697155	0.17306647	2.1363113
Acids, unspecified	µg	35.042196	45.519921	0.20829888	0.07860932	0.17674891	81.025773
Aluminium	g	1.7579977	6.6468122	1.76380228	0.66563636	1.4966482	12.330897
Ammonia	g	0.44324844	2.094769	0.3823541	0.14429553	0.32444089	3.389108
Ammonia, as N	µg	17.598545	22.860564	0.1046098	0.0394784	0.08876509	40.691962
Ammonium, ion	mg	13.56338	17.613528	0.07869399	0.0296981	0.06677462	31.352074
Antimony	mg	0.78245239	3.7239467	1.1001106	0.41516763	0.93348249	6.9551598
Arsenic, ion	mg	7.1218473	34.265123	5.5918766	2.1103025	4.7449037	53.834053
Barium	g	17.803793	85.152069	24.1404883	9.1103105	20.484052	156.69071
Benzene	mg	46.468842	235.75497	34.2158265	12.912614	29.03333	358.38558
Benzene, 1-methyl-4-(1-methylethyl)-	µg	2.7680396	14.043368	2.03815762	0.76917452	1.7294483	21.348188
Benzene, ethyl-	mg	2.6139827	13.261776	1.9247226	0.72636561	1.6331947	20.160042
Benzene, pentamethyl-	µg	2.0760309	10.53252	1.52864481	0.57689093	1.2971088	16.011196
Benzenes, alkylated, unspecified	mg	0.68593556	3.2642731	0.96508899	0.3642122	0.81891191	6.0984218
Benzoic acid	mg	28.099906	142.56211	20.6902811	7.8082466	17.55643	216.71697
Beryllium	mg	0.33534507	1.6711593	0.31126985	0.11746925	0.2641234	2.6993668

Biphenyl	µg	44.411846	211.35021	62.4853026	23.581151	53.020974	394.84949
BOD5, Biological Oxygen Demand	oz	0.17359104	182.2514	0.13161527	0.04966992	0.11168018	182.71796
Boron	mg	86.939552	441.07869	64.0158341	24.158754	54.319684	670.51251
Bromide	g	5.935703	30.114569	4.36975172	1.6490882	3.7078878	45.777
Cadmium, ion	mg	1.1904682	5.2074906	0.82580291	0.31164742	0.70072278	8.2361319
Calcium, ion	g	89.022107	451.62287	65.5209713	24.726774	55.596846	686.48957
Chloride	oz	35.297027	179.06615	25.983512	9.805844	22.047923	272.20045
Chromium	mg	25.164386	114.54296	46.5160807	17.554572	39.470528	243.24853
Chromium VI	mg	0.10588258	0.4819551	0.19572274	0.07386325	0.16607762	1.0235013
Chromium, ion	mg	10.332201	54.347007	3.49771509	1.3199928	2.9679341	72.46485
Cobalt	mg	0.61369032	3.1134964	0.45186958	0.17052978	0.38342721	4.7330133
COD, Chemical Oxygen Demand	g	8.6291357	43.426986	7.0841049	2.6734503	6.0111118	67.824789
Copper, ion	mg	18.0378	43.303736	5.80855995	2.192076	4.9287671	74.270939
Cyanide	µg	2.1088255	10.284973	1.47266725	0.55576573	1.2496099	15.671842
Decane	mg	0.80744239	4.096473	0.5945432	0.22437297	0.50449079	6.2273223
Detergent, oil	mg	25.884186	132.22032	17.1410396	6.4688085	14.544774	196.25913
Dibenzofuran	µg	5.2670318	26.72176	3.87819266	1.4635802	3.2907827	40.621348
Dibenzothiophene	µg	4.4044864	22.302609	3.33501388	1.2585914	2.8298764	34.130577
DOC, Dissolved Organic Carbon	ng	107.60231	139.77573	0.63961289	0.2413817	0.54273401	248.80177
Docosane	µg	29.641313	150.3823	21.8252084	8.2365534	18.519455	228.60483
Dodecane	mg	1.5319995	7.7724447	1.12803837	0.42570721	0.95718019	11.81537
Eicosane	mg	0.42180109	2.1399659	0.31057791	0.11720812	0.26353627	3.2530893
Fluorene, 1-methyl-	µg	3.1524965	15.993864	2.321256	0.87601224	1.9696673	24.313296
Fluorenes, alkylated, unspecified	µg	39.751937	189.17427	55.9291202	21.106932	47.457823	353.42009
Fluoride	mg	220.6221	286.50187	1.2800398	0.48307061	1.0861588	509.97324
Fluorine	µg	20.751452	99.50297	27.5982062	10.415209	23.418047	181.68589
Hexadecane	mg	1.6721665	8.4835612	1.23125917	0.4646614	1.0447666	12.896415
Hexanoic acid	mg	5.8191842	29.523042	4.28476725	1.6170162	3.6357755	44.879786
Hydrocarbons, unspecified	ng	134.63648	174.89321	0.80031024	0.30202682	0.67909135	311.31112
Iron	g	4.0195369	15.374253	3.51490807	1.3264812	2.982523	27.217702
Lead	mg	13.391506	59.868003	11.7521311	4.4351035	9.972096	99.41884
Lead-210/kg	pg	2.8781289	14.601889	2.11923071	0.79977049	1.7982417	22.197261
Lithium, ion	g	18.455658	99.516825	1.04363326	0.3938538	0.88555948	120.29553
m-Xylene	mg	0.83926655	4.2579395	0.61795486	0.23320824	0.52435641	6.4727256
Magnesium	g	17.401962	88.289276	12.8087214	4.833847	10.86865	134.20246
Manganese	g	0.41312178	0.64218116	0.02266075	0.00855188	0.01922845	1.105744
Mercury	µg	31.268033	88.036153	19.3876529	7.3166515	16.451105	162.4596
Metallic ions, unspecified	µg	1.6438388	2.1353518	0.00977136	0.00368758	0.00829134	3.8009409
Methane, monochloro-, R-40	µg	1.1149453	5.6565618	0.82095482	0.30981782	0.69660901	8.5988888
Methyl ethyl ketone	µg	2.2298068	11.312696	1.64185198	0.61961386	1.393169	17.197138
Molybdenum	mg	0.6367668	3.2305711	0.46886448	0.17694344	0.39784798	4.9109938

n-Hexacosane	µg	18.492156	93.818032	13.6162067	5.1385817	11.55383	142.61881
Naphthalene	mg	0.50369881	2.5551195	0.37161891	0.14024421	0.3153317	3.8860131
Naphthalene, 2-methyl-	mg	0.43875553	2.225982	0.32306311	0.12191987	0.2741304	3.3838509
Naphthalenes, alkylated, unspecified	µg	11.240112	53.490199	15.8143628	5.9681375	13.419042	99.931853
Nickel	mg	5.8985656	29.377734	5.51174587	2.0800622	4.6769099	47.545017
Nitrate	ng	11.795698	15.322648	0.07011634	0.02646101	0.05949618	27.274419
Nitrate compounds	µg	0.47490513	0.61690324	0.00282295	0.00106534	0.00239537	1.098092
Nitric acid	mg	1.0652321	1.3837399	0.00633199	0.00238961	0.00537291	2.4630665
Nitrogen, total	mg	33.764671	43.847109	0.19590079	0.07393044	0.1662287	78.04784
o-Cresol	mg	0.79686145	4.042797	0.58674081	0.22142845	0.49787019	6.145698
Octadecane	mg	0.4131111	2.0958777	0.30418026	0.11479373	0.25810764	3.1860704
Oils, unspecified	g	0.66145645	3.0067896	0.4707132	0.17764112	0.39941669	4.716017
p-Cresol	mg	0.85976622	4.3619443	0.63304541	0.23890321	0.53716126	6.6308203
Phenanthrene	µg	5.2020258	25.529665	5.66889974	2.13937	4.8102605	43.350221
Phenanthrenes, alkylated, unspecified	µg	4.660609	22.179218	6.55728248	2.4746343	5.5640845	41.435829
Phenol	mg	4.6862361	21.32967	8.66183948	3.2688671	7.3498751	45.296488
Phenol, 2,4-dimethyl-	mg	0.77589681	3.9364341	0.57130615	0.21560361	0.48477333	5.984014
Phenols, unspecified	mg	8.3450745	44.449196	1.64292881	0.62002024	1.3940828	56.451302
Radioactive species, Nuclides, unspecified	Bq	1970.0814	2558.3656	11.4303056	4.3136506	9.6990157	4553.89
Radium-226/kg	ng	1.001301	5.0799891	0.737297	0.27824643	0.6256224	7.7224559
Radium-228/kg	pg	5.1219637	25.985781	3.77135768	1.423262	3.2001294	39.502493
Selenium	mg	4.9002751	6.8915206	0.24090815	0.09091565	0.20441903	12.328038
Silver	mg	58.097921	294.72493	42.8403424	16.167396	36.351535	448.18213
Sodium, ion	oz	9.9546284	50.499577	7.32659422	2.7649627	6.2168726	76.762635
Solids, inorganic	µg	2.7083223	3.5181191	0.01609889	0.00607552	0.01366048	6.2622763
Solved solids	oz	43.540145	220.88652	32.0476032	12.094354	27.193517	335.76214
Strontium	g	1.5100724	7.66119	1.11191372	0.41962195	0.94349781	11.646296
Sulfate	g	29.522683	46.003959	1.64270129	0.6199344	1.3938898	79.183168
Sulfide	mg	0.54393885	2.4751819	1.00506106	0.37929715	0.85282962	5.2563086
Sulfur	mg	73.389456	372.33397	54.0379719	20.393237	45.853117	566.00775
Suspended solids, unspecified	g	44.922357	197.21081	54.2031576	20.455576	45.993283	362.78519
Tar	ng	26.840556	34.865965	0.15954644	0.06021078	0.13538076	62.061659
Tetradecane	mg	0.67141482	3.4063551	0.49437459	0.18657063	0.4194942	5.1782094
Thallium	mg	0.16500715	0.78540974	0.2318113	0.08748261	0.19670003	1.4664108
Tin	mg	4.2566344	20.966125	4.47640246	1.6893369	3.7983847	35.186883
Titanium, ion	mg	12.020319	57.211419	16.8943464	6.3757096	14.335446	106.83724
Toluene	mg	43.902722	222.736	32.3263874	12.199564	27.430075	338.59475
Vanadium	mg	0.75218475	3.8161335	0.55384625	0.20901447	0.469958	5.801137
Xylene	mg	23.094911	117.00335	17.3598607	6.5513889	14.730452	178.73996
Yttrium	mg	0.18667198	0.94706	0.13745289	0.05187296	0.11663361	1.4396914
Zinc	mg	51.388686	172.12956	40.7571241	15.381215	34.583851	314.24043