Life-Cycle Inventory of Wood Pellet Manufacturing and Utilization in Wisconsin*

John F. Katers
Adam J. Snippen
Maureen E. Puettmann

Abstract

This study summarizes environmental impacts of ''premium'' wood pellet manufacturing and use through a cradle-to-grave life-cycle inventory. The system boundary began with growing and harvesting timber and ended with use of wood pellet fuel. Data were collected from Wisconsin wood pellet mills, which produce wood pellets from a variety of feedstocks. Three groups of manufacturers were identified, those who use wet coproduct, dry coproduct, and harvested timber. Pellet mill data were weight averaged on a per unit basis of 1.0 short ton of ''premium'' wood pellets, and burdens for all substances and energy consumed were allocated among the products on a 0 percent moisture basis. Wood pellets produced from dry coproduct required 60 percent less energy at the pellet mill. However, when considering all cradle-to-gate energy inputs, producing wood pellets from whole logs used the least energy. Pellets from wet coproduct and dry coproduct used 9 and 56 percent more energy across the life cycle, respectively. This study also compared environmental impacts of residential heating fuels with wood pellet fuel. Environmental impacts were measured on net atmospheric carbon emissions, nonrenewable energy use, and global warming potential (GWP). Assuming ''better than break-even'' forest carbon management, cordwood and wood pellet fuels emitted 67.3 and 26.6 percent less atmospheric carbon emissions per megajoule of residential heat across the life cycle than natural gas, the best fossil fuel alternative. Cordwood and wood pellets consumed fewer nonrenewable resources than natural gas, which consumed fewer resources than petroleum-based residual fuel oil. However, wood pellet fuels had a smaller GWP and effect on respiratory health because they have more efficient combustion.

The increasing economic and environmental cost of acquiring energy from fossil fuels has led the United States to explore the development of a variety of renewable and domestic energy sources. One such source is woody biomass, which has found popularity as an alternative energy option, particularly for residential heating because modern wood stove manufacturers often claim over 95 percent efficiency (US Department of Agriculture [USDA] 2009). Wood, as it exists in the forest, is not cost-effective as a main fuel source owing to its low energy density, low bulk density, and high (~50%) moisture content (MC). However, once the wood is dried (to ~6.5% MC) and densified through the pelletization process, the energy content per unit volume nearly doubles and allows for more economical transportation, handling, and combustion in automated appliances (USDA 2009). Research related to the wood pellet industry is in its relative infancy in terms of life-cycle inventory (LCI). As the United States examines the potential for this domestic, abundant, and ''carbon-neutral'' fuel source to meet renewable energy mandates, an

The authors are, respectively, Associate Professor (katersj@uwgb.edu [corresponding author]) and Graduate Student in Environmental Sci. and Policy, Dept. of Natural and Applied Sci., Univ. of Wisconsin, Green Bay; and Consultant, WoodLife Environmental Consultants, LLC, Corvallis, Oregon (Maureen.puettmann@q.com). This paper was received for publication in February 2012. Article no. 12-00018.

* This article is part of a series of nine articles addressing many of the environmental performance and life-cycle issues related to the use of wood as a feedstock for bioenergy. The research reported in these articles was coordinated by the Consortium for Research on Renewable Industrial Materials (CORRIM; http://www.corrim.org). All nine articles are published in this issue of the *Forest Products Journal* (Vol. 62, No. 4).

Forest Prod. J. 62(4):289–295.

LCI for wood pellet production was conducted to provide a metric for evaluating and comparing available renewable fuel options. Others studies on the LCI of wood pellets have been conducted in British Columbia (Pa 2010), Europe (Sikkema et al. 2010), and the Southern United States (Dwivedi et al. 2011), although the focus of each of these studies was different from the current study summarized here.

The purpose of this study was to determine the environmental impacts of ''premium'' wood pellets manufactured in Wisconsin through a cradle-to-grave LCI. The US Environmental Protection Agency (US EPA 2006) defines LCI 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.'' The cradle-to-gate LCI for wood pellet manufacturing documents all material and energy inputs and outputs attributed to every stage of woody raw material processing from forest regeneration, timber harvesting, transportation, energy production, primary wood processing, and pellet manufacturing. Meanwhile the cradle-to-grave LCI includes the combustion of the wood pellets. Although various standards and methods exist to measure the efficiency of residential heating appliances, efficiency has generally been defined as the percentage of available heat that is put into the home divided by the available heat content of the fuel (Houck and Eagle 2006). The difference between the available heat and the heat content of the fuel is due to the phase change of water present in the fuel, incomplete combustion of the fuel, and heat lost out of the stack with the gases, water vapor, and particles created from combustion.

The Pellet Fuels Institute (PFI) is a nonprofit association that serves the pellet industry, which is composed of pellet mills, pellet appliance manufacturers, and industry suppliers. The main goals of PFI are to actively educate consumers about the convenience and practicality of using wood pellet fuel in both residential and commercial applications and to develop industry-wide standards to address the needs of consumers, fuel manufacturers, appliance manufacturers, and the US EPA (Table 1; PFI 2011). Table 1 summarizes the residential/commercial densified fuel standards that have been developed by PFI. In addition, PFI initiated redevelopment of its standards in 2005 and will soon be implementing a program that has been proposed to be incorporated by reference into the US EPA's New Source Performance Standards (NSPS) for Residential Wood Heaters. The US EPA is mandating the regulation of pellet fuel through its NSPS to ensure that fuel pellets will be certified to a specified grade and can be properly matched to the appliances that are permitted to burn them (PFI 2011).

Methods

Data for this analysis was collected using a unit process approach to ensure that only information directly relevant to the scope of the LCI was requested. Wood pellet mill operations were separated into six different process stages: (1) handling delivered logs and processed wood fiber, (2) size reduction, including chipping and hammer milling, (3) drying, (4) pelletizing, (5) cooling, and (6) packaging of final product. These process stages are summarized in Figure 1, along with the various system inputs and outputs. As defined by the Consortium for Research on Renewable Industrial Materials (CORRIM; Wilson and Sakimoto 2005), two boundaries are used to track the environmental impact of producing wood products. The first is the total system boundary (solid line in Fig. 1), which includes both on-site and off-site emissions for all material and energy consumed. The second is the on-site system boundary (dotted line in Fig. 1), which includes the environmental impacts and emissions at the pellet mill complex from the six individual unit processes described previously.

Table 1.—Residential/commercial densified fuel standards (Pellet Fuels Institute [PFI] 2011).

Fuel property	PFI premium	PFI standard	PFI utility
Normative—mandatory			
Bulk density (lb/ft^3)	40.0–46.0	38.0–46.0	38.0–46.0
Diameter (in.)	0.230–0.285	0.230–0.285	0.230–0.285
Diameter (mm)	5.84–7.25	5.84–7.25	5.84–7.25
Pellet durability index	$\geq$96.5	$\geq$95.0	$\geq$95.0
Fines (%) at mill gate	$\leq$0.50	$\leq$1.0	$\leq$1.0
Inorganic ash (%)	$\leq$1.0	$\leq$2.0	$\leq$6.0
Length (% greater than 1.50 in.)	$\leq$1.0	$\leq$1.0	$\leq$1.0
Moisture (%)	$\leq$8.0	$\leq$10.0	$\leq$10.0
Chloride (ppm)	$\leq$300	$\leq$300	$\leq$300
Informative—not mandatory			
Ash fusion properties	Mean value $\pm$ 2 SD		
Heating value (BTU/lb)	Mean value $\pm$ 2 SD		

Existing LCI data from CORRIM and the National Renewable Energy Laboratory (NREL), which was available through the US LCI database, was used 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 coproduct LCI data were available on a regional scale; the Northeast and North Central region data were completed by Hubbard and Bowe (2008) and Bergman and Bowe (2008, 2009) as part of the CORRIM Phase II Final Report (CORRIM 2010). Energy production data were also completed by CORRIM on a regional scale. Average composition of off-site electrical generation was found for the Northeast/North Central region by totaling the amount of the different fuel sources for each of the 20 states in 1,000 kWh and calculating the percentages for each fuel source (US Department of Energy [US DOE] 2006).

Primary data for pellet manufacturing facilities were collected through a detailed questionnaire, developed specifically to address the production of wood pellet fuel. Four of the approximately 10 wood pellet manufacturing companies in Wisconsin completed the questionnaire and provided detailed data about inputs and outputs to their operations for the 2009 calendar year. Average annual pellet production for these four mills was 27,550 tons, with a range of 20,000 to 35,630 tons. Total premium wood pellet production 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. Therefore, approximately 61 percent of Wisconsin's total premium wood pellet production in 2009 was accounted for in the survey, thereby exceeding the minimum CORRIM protocol guideline for data representation (International Organization for Standardization 1998). However, there

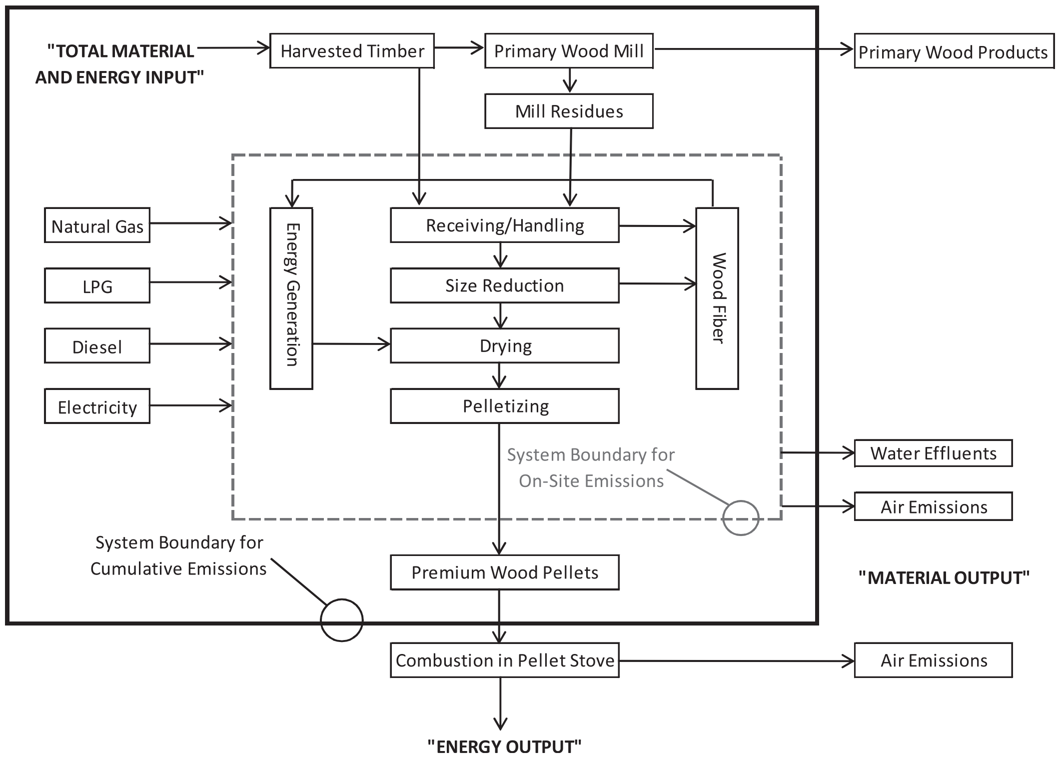

Figure 1.—System boundaries for cradle-to-gate life-cycle inventory (LCI) of wood pellet production where the dotted line represents the LCI boundaries of the pellet mill complex and the solid line represents the cradle-to-gate life-cycle beginning with the growth of timber in the forest, through harvest, primary wood processing, and pelletization.

would be limitations associated with this analysis due to the relatively small sample size and the comparability of Wisconsin to other regions. It should also 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.

Another potential limitation of this research is the allocation of energy for the dry coproducts generated during the production of primary wood products. These dry coproducts could be considered waste products destined for a landfill and not carry a portion of the energy burden associated with creating the primary wood products. However, the coproducts used in pellet production are currently a valued commodity. Therefore, this study strictly focused on allocating all energy and materials associated with producing these feedstock materials, which is consistent with previously established CORRIM protocols. Based on this approach for the analysis, wood pellets may appear to be less favorable from a net energy perspective, which may suggest that an alternative energy allocation method be established for dry coproducts.

The LCI data regarding the extraction, processing, distribution, and combustion of natural gas and fuel oil were obtained through the US LCI database produced by the NREL (2010) and EPA's 2011 US Greenhouse Gas Inventory Report. LCI data regarding wood fuel production were obtained through the US LCI database and manufacturer surveys. Combustion data were obtained from Houck and Eagle (2006). Higher and lower heating values obtained through the US Forest Services' Forest Products Laboratory fuel value calculator were used to determine the energy content and heating efficiency of each fuel, and comparisons were made on a per megajoule basis. The higher heating value is the gross heat available, while the lower heating value is the net heat value. The heating efficiencies for natural gas, residual fuel oil (RFO), air-dried cordwood, and wood pellet heating devices were assumed to be 80, 83, 77, and 83 percent, respectively. Although modern heating appliance manufacturers are claiming higher heating efficiencies across the board, there is a general lack of consensus and data to support such claims. Therefore, a lower efficiency of 83 percent was used for this analysis, which considers the fact that the conversion to more efficient wood pellet heating devices is not complete. The use of sensitivity analysis would be a potential extension of this research to determine the future impacts of higher efficiency heating devices on the life-cycle assessment (LCA).

The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2), a computer program developed by the US EPA 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 noncancer effects, fossil fuel depletion, and land-use effects (PRé Consultants 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

Based on the type of the wood fiber used as feedstock, three production scenarios were identified for wood pellet

Table 2.—Gate-to-gate (onsite) wood inputs (ovendry kilograms) used to produce one short ton of premium wood pellets (average 6.5% moisture wet basis) at Wisconsin pellet mills in 2009.

	Weighted avg. of premium wood pellets from:			Total	
Ovendry wood inputs	Whole logs	Wet coproduct	Dry coproduct	Weighted avg.	Feedstock (%)
Raw materials					
Standing timber, hardwood (m^3)	1.06	—	—	0.30	23.21
Standing timber, softwood (m^3)	0.62	—	—	0.18	5.16
Wet feedstock, hardwood (kg)	—	477.00	—	59.90	7.06
Wet feedstock, softwood (kg)	—	371.66	—	46.70	5.50
Dry feedstock, hardwood (kg)	—	—	849.28	501.67	59.07
Total wood in pellets (kg)	850.40	848.66	849.28	849.45	100.00
Wood used for energy (kg)	149.78	136.21	160.50	154.50	
Total wood (ovendry kg)	1,000.18	984.87	1,009.78	1,003.95	

production. Some wood pellet manufacturers harvested and processed their own timber as feedstock. Other wood pellet manufacturers purchased wet coproducts (MC > 35%) or dried coproducts (MC < 35%) from primary wood processing facilities for feedstock. Wood pellet manufacturers also used 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.

All cradle-to-gate woody biomass raw material inputs are summarized in Table 2 on an ovendry kilogram of wood per short ton (2,000 lb or 907.18 kg) of premium wood pellets basis at 6.5 percent moisture content. This table represents a weighted average of survey data based on feedstock, rather than data for any one mill. A weighted Wisconsin average was also calculated to show the most common trends in raw material and energy usage scenarios during the survey period, with the percentage of the total feedstock used being reported to identify the most significant inputs.

Survey results indicated that pellet producers who harvest their own timber for feedstock used a weighted average of 1.06 m^3 of hardwood and 0.62 m^3 of softwood as raw material to produce one short ton of wood pellets. The CORRIM Phase II average density values for hardwood and softwood timber in the (Northeast/North Central) United States were 580 and 380 kg/m^3, respectively. In order to dry the wet coproduct feedstock prior to pelletization, 149.78 kg of additional wood was combusted, resulting in a total wood consumption of 1,000.18 kg to produce one short ton of wood pellets. Pellet producers who used wet coproduct feedstock used a weighted average of 477.00 kg of hardwood and 371.66 kg of softwood as raw material to produce one short ton of wood pellets. An additional 136.21 kg of wood was required to dry the wet coproduct feedstock before pelletization, resulting in a total wood consumption of 984.87 kg to produce one short ton of wood pellets. Pellet producers who used source-dried feedstock used a weighted average of 849.28 kg of dry hardwood as raw material for one short ton of wood pellets. An additional 160.50 kg of wood was consumed along the life cycle to dry the raw materials, resulting in a total wood consumption of 1,009.78 kg to produce one short ton of wood pellets. The average wood in–to–wood out ratio for producing wood pellets was found to be 1.18:1.

A summary of the cradle-to-gate energy requirements for producing one short ton of Wisconsin wood pellets is provided in Table 3. Data are listed by harvesting of timber, processing lumber and the generation of coproducts at primary forest products mills, transportation, and the production of wood pellets. Wood pellet production data were obtained from the survey of wood pellet manufacturers in Wisconsin, while the remaining data were from CORRIM Phase II. Percentages of total fuel and energy (megajoules) are listed to identify the most significant inputs by each individual process as well as the entire life cycle. To convert volume or mass of a fuel to its energy value, higher heating values (HHVs) were used. HHV represents the energy content of a fuel with the combustion products, such as water vapor, brought to 25°C (77°F), while the lower heating value ignores the energy produced by the combustion of hydrogen in fuel. Transportation was also determined in ton-kilometers (tkm), or the hauling of one metric ton (1,000 kg) of cargo over the distance of 1 km. The average for Wisconsin was 199.87 tkm/ton, with whole logs being the lowest at 99.28 and dry coproducts being the highest at 241.40. A complete cradle-to-gate LCI tracking material and energy inputs as well as air and water emission outputs for each production scenario was also completed but is not included in these results.

Total cradle-to-grave nonrenewable material energy inputs (megajoules) for the production of 1 MJ of residential heat using cordwood, wood pellets, natural gas, and RFO are listed in Table 4. The 1 MJ of fossil fuel–based energy contained within the raw materials is also included in the LCI of natural gas and RFO. Cordwood uses the least amount of nonrenewable energy to produce 1 MJ of heat (0.035 MJ), followed by wood pellets (0.307 MJ), natural gas (1.411 MJ), and RFO (1.527 MJ).

As shown in Figure 2, total atmospheric greenhouse gas (GHG) emissions associated with producing 1 MJ of residential heat are highest with wood pellets (0.1459 kg CO_2 eq), followed by cordwood (0.1438 kg CO_2 eq), RFO (0.1136 kg CO_2 eq), and natural gas (0.0780 kg CO_2 eq). However, the model assumes that trees used for wood feedstock are part of a sustainable forestry operation allowing for biogenic carbon to be sequestered in new growth of woody biomass. Therefore, the only net carbon emissions for cordwood and wood pellets are due to the combustion of fossil fuels across the life cycle, or 0.0255 and 0.0572 kg CO_2 eq, respectively.

Discussion

The average ton of premium wood pellets produced in Wisconsin was produced mostly from source-dried hard-

Table 3.—Cradle-to-gate energy consumption by process for producing one short ton of wood pellets at Wisconsin pellet mills in 2009.

Process	Energy consumption (weighted avg. in MJ) to produce premium wood pellets from:			Total	
	Whole logs	Wet coproduct	Dry coproduct	Weighted avg.	Energy (%)
Timber harvest					
Coal	10.92	5.08	7.13	7.76	2.84
Natural gas	16.57	7.71	10.83	11.77	4.31
Crude oil	353.09	164.32	230.66	250.78	91.87
Uranium	3.75	1.74	2.45	2.66	0.98
Total energy	384.34	178.86	251.07	272.97	100.00
Coproduct production					
Coal	—	415.74	1,548.80	967.98	23.10
Natural gas	—	79.38	1,051.00	631.40	15.07
Crude oil	—	122.89	566.48	350.38	8.36
Uranium	—	146.88	547.11	341.94	8.16
Wood (oven dry)	—	1.35	3,211.51	1,899.08	45.32
Total energy	—	766.24	6,924.89	4,190.78	100.00
Transportation					
Coal	3.58	8.33	8.70	7.32	2.84
Natural gas	5.44	12.65	13.20	11.12	4.31
Crude oil	115.85	269.50	281.17	236.83	91.87
Uranium	1.23	2.86	2.99	2.51	0.98
Total energy	126.10	293.35	306.05	257.79	100.00
Total off-site energy	510.48	1,238.45	7,482.00	4,721.55	
Wood pellet production					
Coal	1,693.59	1,573.56	1,294.30	1,441.59	39.30
Natural gas	278.23	269.95	219.22	240.71	6.56
Crude oil	209.68	467.17	317.08	270.95	7.39
Uranium	598.46	555.96	457.32	509.38	13.89
Wood (oven dry)	2,995.60	2,722.00	22.63	1,205.10	32.86
Total on-site energy	5,775.57	5,588.64	2,310.54	3,667.74	100.00
Total cradle-to-gate energy consumption					
Nonrenewable energy	3,290.40	4,103.74	6,558.40	5,285.10	63.00
Renewable energy	2,995.60	2,723.35	3,234.14	3,104.18	37.00
Total energy (MJ)	6,286.00	6,827.09	9,792.54	8,389.28	100.00
Total energy (BTU)	5,957,981	6,470,830	9,281,537	7,951,505	100.00

wood coproducts (59.17%), followed by hardwood whole logs (23.21%), wet hardwood coproducts (7.06%), wet softwood coproducts (5.50%), and softwood whole logs (5.16%). Therefore, it can be stated that the vast majority (89.44%) of wood pellets produced in Wisconsin are made of hardwood materials. Wood pellets produced from source-dried raw materials required the most fuel wood for drying as a result of the more energy intensive drying procedures used by the primary hardwood product manufacturers, who are drying lumber as opposed to wood chips or shavings. Pellets produced from wet coproduct consumed the least amount of fuel wood per ton of pellets produced, likely because of the increased opportunity for air drying that occurs during storage and transportation.

On-site energy consumption for the production of premium wood pellets was lowest using source-dried coproduct (2,310 MJ), followed by wet coproduct (5,588 MJ), and whole logs (5,775 MJ). However, the cost of predried feedstocks is significantly more than wet coproducts or whole logs, so a reduction in overall costs may not be achieved. Renewable wood fuel accounted for a significant amount on-site energy use (32.86%) and was primarily used in the drying process, which would be eliminated by receiving predried feedstocks. Electricity accounted for over a third of on-site fuel consumption and was primarily used for fans, conveyors, air emission reduction equipment, and the pelletization equipment. The weighted average on-site energy consumption for Wisconsin pellet producers was 3,668 MJ per short ton of wood pellets produced. As shown in Table 3, cradle-to-gate energy consumption for the production of premium wood pellets was lowest using whole logs (6,286 MJ), followed by wet coproduct (6,827 MJ), and source-dried coproduct (9,793 MJ). The weighted average energy consumption for

Table 4.—Nonrenewable energy inputs, including nonenergy material inputs, per megajoule of energy output for residential heating in Wisconsin.

Source	Amount of input to produce heat (MJ/MJ)			
	Cordwood	Wood pellets	Natural gas	Residual fuel oil
Coal	0.001	0.140	0.013	0.030
Natural gas	0.002	0.052	1.383	0.058
Crude oil	0.032	0.066	0.011	1.429
Uranium	0.000	0.050	0.004	0.010
Total	0.035	0.307	1.411	1.527

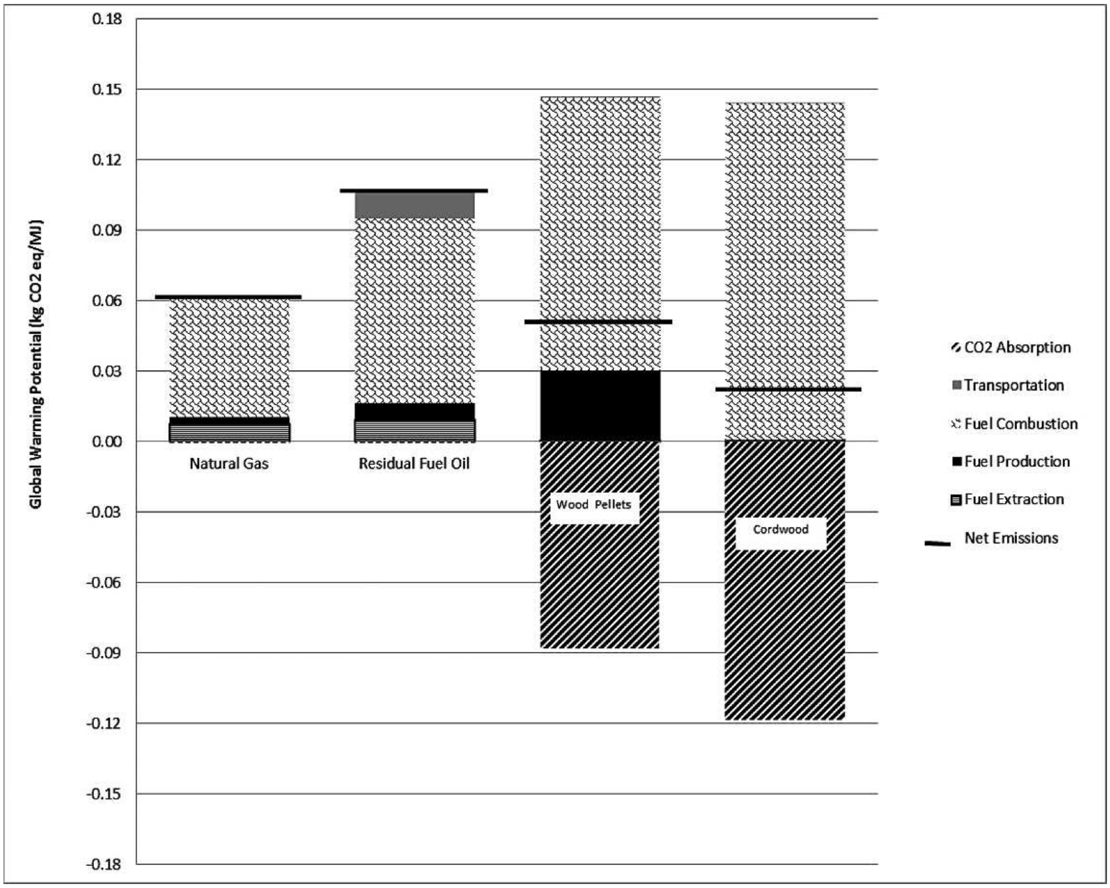

Figure 2.—Total cradle-to-grave atmospheric greenhouse gas emissions (kilogram CO_2 equivalent) associated with producing 1 MJ of residential heat using renewable and nonrenewable fuel sources.

producing one ton of premium wood pellets in Wisconsin was 8,389 MJ.

The largest contributing factor to overall energy 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. When considering cradle-to-gate energy consumption, wood accounts for 37 percent of total energy, while coal accounts for nearly 29 percent. This trend is due to electricity being produced primarily from coal-fired power plants in the Northeast/North Central United States. 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 moisture contents, denser wood, and longer, slower kiln-drying schedules all contributed to higher primary manufacturing energy consumption for hardwood coproducts (Puettmann et al. 2010).

The gross energy content of one short ton of premium wood pellets is approximately 16,400,000 BTUs. Therefore, the energy return on investment 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 coproduct (1.77), wet coproduct (2.53), whole logs (2.75), and the Wisconsin weighted average (2.06). These values consider all materials and energy invested into producing wood pellet fuel.

When considering the potential for our forest biomass resources to mitigate carbon emissions, it must be stated that all carbon emissions are significant, whether biogenic or from nonrenewable fossil fuels. Managing forests for carbon storage involves a ‘‘better than break-even’’ strategy to maximize the potential for biological carbon sinks. Assuming this is part of woody biomass energy policy, the carbon contained in wood would remain in the biogenic carbon cycle, yielding only net atmospheric carbon emissions associated with the fossil fuels used in biomass fuel processing. Under this assumption, substituting wood pellets for the ‘‘cleanest’’ burning fossil fuel, natural gas, results in a 26.6 percent reduction in life-cycle GHG emissions and substituting wood pellets for RFO yields a 49.7 percent reduction in life-cycle GHG emissions. Substituting cordwood for natural gas and RFO results in a 67.3 and 77.6 percent reduction in life-cycle atmospheric GHG emissions, respectively.

Conclusions

An LCI of wood pellet fuels produced in Wisconsin was conducted to serve as a reliable source of data upon which to base business and policy decisions. Based on the results of the pellet industry survey, Wisconsin wood pellets are primarily produced from hardwood feedstock (~90%). On-site energy consumption using source-dried feedstock is approximately 60 percent less than using whole logs or wet coproduct 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 wet coproduct and dry coproduct used 9 and 56 percent more energy, respectively, with the larger amount for dry coproducts attributed to the more inefficient drying process used to dry lumber instead of chips or shavings. It can also be stated that the energy allocation for dry coproducts may be over weighted based on the dollar value of the primary products relative to the energy value of the dry coproducts, which may warrant further discussion in terms of how entrained energy is allocated from an LCI standpoint. It should also be noted that, on average, 37 percent of the energy used to produce wood pellet fuel comes from wood fuel, which is a renewable source of energy.

When considering global warming potential (GWP), cordwood has a lower GWP than wood pellets, but other environmental benefits of wood pellets are realized in more efficient combustion, yielding less carbon monoxide and particulate matter emissions. Wood fuels yielded better GWP values in general compared with natural gas and RFO because of the amount of carbon that was biogenic, and therefore sequestered, at the beginning of the life cycle.

Although there are several limitations to this research, primarily a small sample size and the methodology used to allocate energy from dry coproducts, the results still indicate that wood pellets offer a number of advantages from an LCA standpoint over fossil fuels. This is consistent with several previous studies that showed switching from firewood to wood pellets would reduce energy consumption, improve human health, improve ecosystem quality, and help mitigate climate change (Pa 2010, Sikkema et al. 2010, Dwivedi et al. 2011). The information contained in this LCI report should be used as a benchmark for future LCIs involving wood pellets or other renewable and nonrenewable fuels, since 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. Future work should include a more detailed sensitivity analysis on key aspects of this analytical approach, including the efficiency of wood pellet heating devices and the allocation of entrained energy from dry coproducts, because agreement on these variables will be necessary to maintain consistency.

Literature Cited

Bare, J. C., G. A. Norris, D. W. Pennington, and T. McKane. 2003. TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *J. Ind. Ecol*. 6(3–4):49–78.

Bergman, R. B. and S. A. Bowe. 2008. Environmental impact of producing hardwood lumber using life-cycle inventory. *Wood Fiber Sci*. 40(3):448–458.

Bergman, R. B. and S. A. Bowe. 2009. Life-cycle inventory of softwood lumber manufacturing in the northeastern and north central United States. CORRIM Phase II Final Report: Module D. Consortium for Research on Renewable Industrial Materials. http://www.corrim.org/pubs/reports/2010/phase2/index.asp. Accessed August 22, 2012.

Consortium for Research on Renewable Industrial Materials (CORRIM). 2010. Life cycle environmental performance of renewable building materials in the context of residential construction. CORRIM Phase II Final Report. http://www.corrim.org/pubs/reports/2010/phase2/index.asp. Accessed August 22, 2012.

Dwivedi, P., R. Bailis, T. Bush, and M. Marinescu. 2011. Quantifying GHG emissions of wood pellet production in the Southern United States and its subsequent utilization for electricity production in the Netherlands. *Bioenergy Res*. 4(3):180–192.

Houck, J. E. and B. N. Eagle. 2006. Task 6 technical memorandum 4 (final report): Control analysis and documentation for residential wood combustion in the MANE-VU region. http://www.marama.org/publications_folder/ResWoodCombustion/RWC_FinalReport_121906.pdf. Accessed August 22, 2012.

Hubbard, S. S. and S. A. Bowe. 2008. Life-cycle inventory of solid strip hardwood flooring in the Eastern United States. CORRIM Phase II Final Report: Module E. Consortium for Research on Renewable Industrial Materials. http://www.corrim.org/pubs/reports/2010/phase2/index.asp. Accessed August 22, 2012.

International Organization for Standardization (ISO). 1998. Environmental management—Life-cycle assessment—Goal and scope definition and inventory analysis. ISO 14041. First edition 1998-10-01. ISO, Geneva.

National Renewable Energy Laboratory (NREL). 2010. U.S. life-cycle inventory database. https://www.lcacommons.gov/nrel/search. Accessed August 22, 2012.

Pa, A. 2010. Development of British Columbia wood pellet life cycle inventory and its utilization in the evaluation of domestic pellet applications. Master's thesis. University of British Columbia, Vancouver.

Pellet Fuels Institute (PFI). 2011. PFI standards. http://pelletheat.org/pfi-standards/. Accessed August 22, 2012.

PRé Consultants. 2008. SimaPro 7 database manual: Methods library. http://www.pre-sustainability.com/content/databases#Impactassessment. Accessed August 22, 2012.

Puettmann, M. E., R. Bergman, S. Hubbard, L. Johnson, B. Lipke, E. Oneil, and F. G. Wagner. 2010. Cradle-to-gate life-cycle inventory of US wood products production: CORRIM Phase I and Phase II products. *Wood Fiber Sci*. 42(CORRIM Special Issue):15–28.

Sikkema, R., M. Junginger, W. Pichler, S. Hayes, and A. Faaij. 2010. The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels Bioprod. Biorefining* 4(2):132–153.

US Department of Agriculture (USDA). 2009. North America's wood pellet sector. FPL-RP-656. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.

US Department of Energy (US DOE). 2006. Net generation by energy source by type of producer. US DOE, Washington, D.C. http://www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls. Accessed August 22, 2012.

US Environmental Protection Agency (US EPA). 2006. Life cycle assessment: Principles and practice. US EPA, Washington, D.C. http://www.epa.gov/nrmrl/std/lca/lca.html. Accessed August 22, 2012.

Wilson, J. B. and E. T. Sakimoto. 2005. Gate-to-gate life-cycle inventory of softwood lumber production. *Wood Fiber Sci*. 37(CORRIM Special Issue):58–73.