

Woody Biomass Substitution for Thermal Energy at Softwood Lumber Mills in the US Inland Northwest*

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Abstract

Using life-cycle inventory production data, the net global warming potential (GWP) of a typical inland Northwest softwood lumber mill was evaluated for a variety of fuel types used as boiler inputs and for electricity generation. Results focused on reductions in carbon emissions in terms of GWP relative to natural gas as the fossil alternative. Woody feedstocks included mill residues, forest residuals, and wood pellets. In all fuel-substitution scenarios, increasing the use of biomass for heat generation decreased GWP. Using woody biofuels for electricity production is somewhat less effective in lowering carbon emissions than when used for heat energy. Heat generation at the mill under the current practice of using about half self-generated mill residues and half natural gas resulted in a 35 percent reduction in GWP over 100 percent natural gas. The greatest reduction in GWP (66%) was from increased use of forest residuals for heat energy, eliminating the use of fossil fuels as a direct heating fuel at the mill. We summarize the results by documenting that greater use of woody biomass for heat energy will reduce carbon emissions over fossil-based fuels.

Recent technological advances have provided numerous options for the conversion of biomass to energy. These technologies include electricity production, pellet production for residential and industrial heating, woody and agricultural residue to liquid fuels, and steam generation for industrial heating or manufacturing operations. The scientific community has conflicting opinions on the use of biomass for energy, however, both for economic reasons and, more commonly, because of the environmental impacts. The challenge is to use wood resources sustainably while improving our economy, yet without adversely affecting our environment. Increasing the use of wood waste as an energy fuel can reduce our need for imported fossil fuels, resulting in many benefits to the economy while at the same time reducing net carbon emissions. Unfortunately, the balancing acts between economics and environmental improvements have been problematic. On one hand, federal agencies are setting greenhouse gas (GHG) reduction standards for

acceptable substitutes for fossil fuels. The US Environmental Protection Agency (US EPA) under the 2007 Energy Independence and Security Act (EISA) has set the threshold for cellulosic fuels at a minimum of 60 percent reduction in fossil emissions (EISA 2007, Sissine 2007). However, many critics are claiming that the use of woody biomass for energy actually releases more carbon into the atmosphere because of management, harvesting, and conversion (Schulze et al. 2012). Some argue that biofuels from woody resources are not carbon neutral because of decreases in the forest stand inventory, which reduces carbon sinks, together with the use of fossil fuels for stand management and harvesting, which emit carbon back to the atmosphere (Heiken 2007, Schulze et al. 2012).

Life-cycle assessment (LCA) is a holistic approach to quantify environmental impacts for every stage of production and use of a product, i.e., from cradle to grave. Comparing the environmental benefits of biofuels requires

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measurements across the total life cycle, from forest/biomass growth through combustion (Lippke et al. 2011). Depending on the fuel combusted, carbon is emitted to the atmosphere as “biogenic CO₂” or “fossil CO₂.” Carbon dioxide is also sequestered, absorbed from the atmosphere by living trees during photosynthesis, and extended to carbon stored in biomass. When biogenic CO₂ is released during combustion, it is considered equal to the amount of CO₂ absorbed during tree growth. Under sustainable forest management, the harvest does not exceed the growth in the forest. Therefore, carbon emissions from the combustion of woody biomass are considered carbon neutral (US EPA 2006, Beauchemin and Tampier 2008, Fernholz et al. 2009). When biofuels replace fossil fuel, the net impact over the long term is a sustainable reduction in CO₂ levels in the atmosphere, some well above the 60 percent threshold reduction in carbon emissions set by the EPA (EISA 2007, Sissine 2007). With the increasing interest in biofuels, it is important to understand the relative impacts of different biofuel uses on carbon. With softwood lumber manufacturers in the US Inland Northwest (INW) as an example (Puettmann et al. 2010b), the objective of this study was to evaluate the different impacts on net carbon emissions from the use of mill residues, wood pellets, and forest residuals as substitutes for natural gas for either heat production for drying or the generation of electricity. Cogeneration for the woody feedstocks was not part of this assessment because the mills in the INW region did not have these operations. We wanted to show the carbon impacts of using waste residues for energy in the mills to offset fossil fuels and to address the issue of collection options for forest residuals for direct heat energy or for electricity. The process models assessed used mill generated wood waste for either direct heat generation or electricity, not both.

In the western United States, wood is an important part of the economy. Western softwood lumber production uses self-generated mill residues for about half of the energy required for drying, with the remainder from natural gas (Milota et al. 2005, Puettmann et al. 2010a). Previous LCA studies have shown that wood drying is the dominant use of energy in the production of lumber, regardless of the geographical region in which the lumber is produced (Milota et al. 2005, Bergmann and Bowe 2010, Puettmann et al. 2010b). Cradle-to-gate impact assessments for softwood lumber consistently show that manufacturing energy is the dominant energy life-cycle stage, consuming 89 to 92 percent of the total energy (Puettmann et al. 2010a). With nearly half of the fuel coming from natural gas, significant carbon emission reductions are possible by converting softwood lumber mills to all woody biomass energy, at least for drying. This article will focus on the impacts on net global warming potential (GWP) of softwood lumber production from cradle to gate, using fuel substitution as boiler inputs for steam and electricity generation alternatives.

GWP is an indicator, expressed as a factor of CO₂, that reflects the relative effect of a GHG in terms of climate change over a fixed time period, commonly 20, 100, or 500 years. For example, the 20-year GWP with substitution for electricity at the mill of methane is 56, which means if the same weights of methane and carbon dioxide were introduced into the atmosphere, methane will trap 56 times more heat than will the carbon dioxide over the next 20 years. Values were converted to kilograms of carbon

dioxide equivalents (kg CO₂ eq). GWP compares the amount of heat trapped by a certain mass of the gas in question with the amount of heat trapped by a similar mass of carbon dioxide.

Questions remain on whether it might be better to raise the share of biofuel in solid wood processing facilities to displace the emissions from natural gas or possibly even lower the biomass share. For example, collecting more forest residuals as a part of the harvest for boiler inputs has the potential to provide as much as four times the energy needed for processing energy, resulting in better than self-sufficiency in solid wood production mills (Lippke et al. 2011). Although the cost of collecting forest residuals has been the primary deterrent to their use as biofuel feedstocks, this may not be an obstacle if the value of carbon is increased through incentives to reduce carbon emissions or if the cost of fossil fuels or their emissions increases. When forest residuals are densified at the landing, hauling costs are reduced, potentially making residuals more competitive in serving energy needs, especially where hauling distances have been the primary obstacle to their use (Johnson et al. 2012).

Common forest practices in the West for forest residuals have been to collect the debris into “slash piles” and burn them on site or leave the piles to decompose. Lee et al. (2010) reported that in the Pacific Northwest, one-third of a ton of woody biomass residuals is generated for every ton of merchantable logs harvested; however, there is substantial variation in the amount, depending on the source of the biomass. Oneil and Lippke (2009) found that residuals for eastern Washington were almost equal to the volume of merchantable logs, but only about 24 percent of the total standing volume was likely to be recoverable. In either case, if made accessible and affordable, this material could provide a significant source of energy.

Alternatively, it might be better, both economically and environmentally, to increase the use of natural gas in lumber mills and use the forest residuals for electricity production or to bypass the mill completely and convert the residuals to liquid fuels. The conversion of biomass to electricity could offset the wood processing use of fossil fuels by reducing the fossil emissions generated for electricity production. Because of the variety of fuel sources used for electricity production, air emissions vary substantially across the country and are heavily influenced by the availability of alternative energy sources, such as hydropower. These consequences should be noted when considering different fuels for electricity production. The development of large-scale biomass-to-electricity utilities could be limited based on the cost of collection, sustainable feedstock resources, and environmental impacts. Small electric utilities or on-site electricity generation, such as cogeneration at wood product mills, could provide the production of electricity from non-fossil fuel sources, resulting in reductions in GHG emissions. Although cogeneration is not prevalent in INW softwood lumber mills, several US sawmills do generate some of their own electricity (Bergman and Bowe 2010), which does offset the use of electricity from the grid. Bergman and Bowe reported that, on average, 18 percent of the total wood waste used in the mills went to cogeneration. In the northeastern United States, where coal is the primary fuel for electricity generation (63% share), using mill residues for electricity generation could significantly reduce carbon emissions.

Methods

With a previously published life-cycle inventory (LCI) on the manufacture of softwood lumber produced in the INW (Puettmann et al. 2010b), fuel feedstock alternatives such as boiler inputs were compared using GWP as the performance metric. Energy requirements collected from INW softwood lumber manufacturers had an average fuel mix of 54 percent self-generated wood fuel and 46 percent natural gas used as boiler inputs for drying lumber. With the LCI data for softwood lumber production, alternative fuels were substituted as boiler inputs for determining the impact on GWP. All alternatives were modeled using the SimaPro (PRé Consultants 2012) LCA software package. We assessed the GWP (expressed in kg CO₂ eq) of the GHG emissions released by each feedstock alternative (mill residues, natural gas, forest residuals, pellets).

System boundaries

The system boundary encompassed the product manufacturing processes, including material (logs), electricity, and fuels required to produce one cubic meter of finished product (Fig. 1). The cumulative system boundary (cradle to gate) included all upstream flows of energy, fuel, and raw material production (Puettmann et al. 2010a). Fuel combustion emissions and sawmill manufacturing emissions (including dryer and boiler) were included. Log input to sawmills contained both wood and the accompanying bark. Detailed descriptions of feedstock system boundaries can be found in Puettmann et al. (2010b) for softwood lumber, Johnson et al. (2012) for forest residues, and Katers et al. (2012) for pellet production.

Fuel substitutions at the boiler included the mass allocation of the fuel from producing pellets and forest residues. In the current case, where self-generated wood fuels (mill residues) were used, the allocation of the fuel wood portion was on a mass basis at the process center in which the fuel wood was produced, with 100 percent of the fuel wood allocated to the production of rough dry lumber (prior to planning). For a complete description of the softwood lumber production, including boiler operations, see Puettmann et al. (2010b).

The reference for the boiler substitution feedstocks was that a unit consisted of 1 m³ of finished planed dried

softwood lumber. The conversion factor for 1,000 board feet (MBF) was equal to 1.622 m³.

Background of data source

INW softwood lumber production.—Softwood lumber is typically dried to a moisture content of 15 percent. Puettmann et al. (2010b) reported approximately 50 percent of the bark generated during debarking, as well as other wood waste sources from downstream processes, were used as wood fuel in the boiler for steam generation. The total wood fuel burned was 110 kg/m³ at 50 percent moisture content on a wet basis or 55 kg/m³ of oven-dry weight wood fuel. Oven-dry wood fuel has an energy content of 20.9 MJ/kg. Wood fuel (55 kg) and natural gas (25 m³) were the fuel sources consumed in the boiler, meeting 54 and 46 percent of the energy needed, respectively. The INW resource-management scenarios included state or private and national forest ownership for softwood logs. The LCI used an average management and harvest volume scenario that represented 9, 30, and 61 percent from national forest (50:50, gentle:steep slopes), state or private dry sites (90:10, gentle:steep slopes), and state or private moist sites (70:30, gentle:steep slopes), respectively (Oneil and Lippke 2009). Forest-management practices included in the harvesting life-cycle stage were regeneration, seedling growth, thinning (precommercial and commercial), and final harvest, as well as associated equipment use. The system boundary for softwood lumber production included forest management and harvesting, lumber production, and transportation to the mill. LCI data for natural gas were obtained from the US LCI database (National Renewable Energy Laboratory [NREL] 2012). Emissions from the combustion of natural gas were based on AP-42 (US EPA 1998). The natural gas data included extraction, production, combustion, and transportation. Natural gas has an energy content of 38.08 MJ/m³. The total heat energy requirement for INW softwood lumber was 2,124 MJ/m³.

Pellet production.—Wood pellet LCI data were obtained from Katers et al. (2012). The system boundary included extraction or feedstock collection, pellet production, combustion of wood pellet fuel, and transportation of feedstocks to pellet manufacturing. Data were based on surveys of Wisconsin wood pellet mills. Wood pellet feedstock included whole log collection and wet and dry mill residues. The energy content of wood pellets was 19.1 MJ/kg.

Forest residues.—Forest residues were collected after conventional logging operations in the INW (Johnson et al. 2012). The average forest type was moist-cold forest with gentle slopes on state or private land. Total residue generated through the primary harvesting activity was 72.1 tonnes/hectare (t/ha; tonnes = metric tons). The primary harvest involved delivery of whole trees to the landing, so the resulting residues were piled at that location. Residue recovery involved grinding at the landing and transportation. A transportation distance of 80.5 km (50 mi) was used from the landing to a feedstock use point. Total residue recovered was 32.5 t/ha (14.48 bone dry tons [BDT] per acre).

Boiler substitution scenarios

Four feedstock alternatives for producing thermal energy at the mill were modeled to assess their impact on GWP. Each alternative was evaluated in a separate scenario.

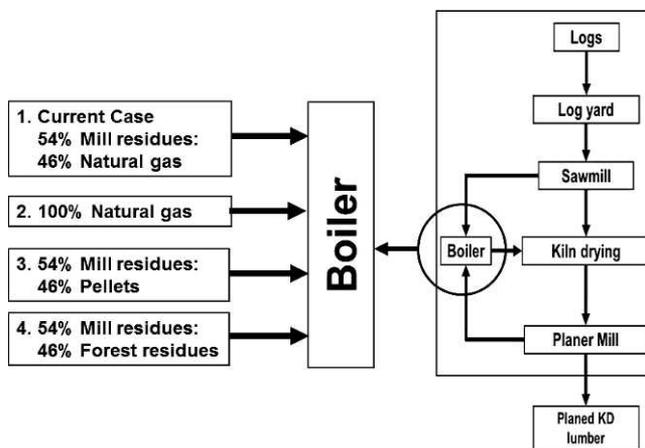


Figure 1.—System boundary for softwood lumber production with boiler substitution scenarios. KD = kiln dried.

Puettmann et al. (2010b) reported that the average INW boiler feedstocks used 54 percent mill residues and 46 percent natural gas. This average mix of fuels (labeled the current case) was used in Scenario 1 as the source of thermal energy required to dry the softwood lumber. The second scenario increased the natural gas use to 100 percent of the energy requirements. This scenario rerouted the flow of coproducts produced at the mill from going to the boiler (sawdust, bark, shavings) to a sold coproduct (Fig. 1). The third scenario considered wood pellets as a substitution for natural gas, resulting in 46 percent wood pellets and 54 percent mill residues. The fourth scenario was also a 100 percent biomass-fueled boiler that substituted forest residuals for the natural gas, resulting in a fuel mix of 54 percent mill residues and 46 percent forest residuals.

Electricity generation substitution

Electricity is consumed throughout the lumber manufacturing process to run fans, hydraulic conveyors, saws, planers, and sorters. All four scenarios consume electricity for the production of lumber from an average (2008) western electricity grid production system (US LCI 2012; Fig. 2). Puettmann et al. (2010b) reported that the average INW softwood lumber mill consumed 76.23 kWh/m³ of electricity from the western grid production system. In this region, electricity generation primarily comes from coal, hydropower, and natural gas at 35, 30, and 25 percent, respectively (NREL 2012).

To evaluate the best use for woody biomass as a fuel for INW mills, two additional scenarios were modeled to evaluate the environmental tradeoffs of using woody biomass for heat generation, as in the mill boiler, or as a feedstock for electricity generation. The fifth scenario used the current case (54% mill residues; 46% natural gas) for heat generation and forest residuals transported to the mill for electricity generation (Fig. 2). The sixth scenario assumed that all the mill residues generated on site were used for electricity generation to reduce emissions, thus requiring all the heat needed for drying lumber to be produced from natural gas.

Data for the electricity production from biomass were obtained from the US LCI database (US LCI 2012). For Scenarios 5 and 6, the electricity generation was modeled as a process of biomass gasification followed by a gas turbine. The process for electricity generation from wood waste was

not assumed to be a process used at sawmills, but more of an average US electricity generation process. The LCI data included the extraction of fuels and raw materials through the production of electricity. Process and fuel emissions were reported together in the original data source and could not be separated.

GWP impact assessment

The LCA results include both an LCI and a life-cycle impact assessment (LCIA). The data include cradle-to-gate environmental impacts from energy and raw materials use, transport, lumber production, and combustion of fuels and feedstocks. SimaPro (PRé Consultants 2012) was used to develop the individual processes. GWP was determined using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2 v.3.0; Bare et al. 2003). TRACI is a midpoint-oriented LCIA methodology developed by the US EPA specifically for the United States using input parameters consistent with US locations, and it uses a 100-year time frame. All calculations in this report for CO₂ absorption are based on 52 percent carbon content for the woody feedstocks (Puettmann et al. 2010b).

Results

Results for all boiler substitution scenarios are references to 1 m³ of planed dried softwood lumber produced in the INW. Scenario 1 resulted in a GWP of 124 kg CO₂ eq fossil carbon emissions (Fig. 3; Table 1). When the substitution was made to use 100 percent natural gas (Scenario 2), GWP increased 67 kg of fossil carbon emission (+54%) more than the current case. Switching fuel input to wood pellets to displace the natural gas fuel (Scenario 3) decreased fossil emissions by 41 kg CO₂ eq (-33%). Finally, substituting forest residuals for natural gas (Scenario 4) decreased GWP emissions by 58 kg, a reduction in kilograms of carbon dioxide equivalents of 47 percent over the current case.

The usual alternative to using these forest residuals is to eliminate them by open burning or pile burning, where emissions are not controlled and the heat energy cannot be captured. This practice makes the use of forest residuals collection as an energy feedstock particularly attractive. Pellets were less efficient in reducing emissions because of the additional energy (primarily fossil fuel-based) needed to produce pellets; however, hauling costs may be lower for pellets than for collecting forest residuals, making pellets more cost competitive in some situations.

The fuel alternatives analysis showed that biofuels are effective in reducing GWP when substituted for fossil fuels, which is one of the primary objectives in using them (Fig. 3). Lee et al. (2010) reported that the use of forest residuals for energy over on-site slash burning or decomposition reduced GWP emissions by at least 20 percent. The reduction in GHG emissions associated with GWP when biofuels displace fossil fuels depends on the energy content of the biofuel and the quantity of the fossil emissions displaced (Lee et al. 2010). The higher the energy content of the biofuel used, the greater the reduction in fossil emissions and GWP. GWP from gathering, chipping, and hauling forest residuals made up less than 3 percent of the total cradle-to-gate GWP for the combustion of forest residuals. Lee et al. reported similar findings of less than 4 percent for the processing of forest residuals.

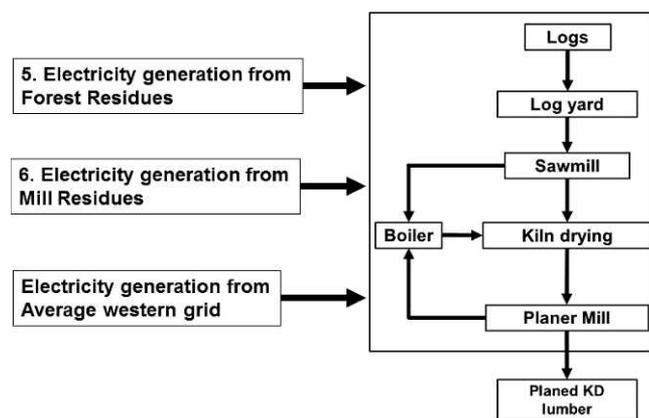


Figure 2.—System boundary for softwood lumber production with electricity generation substitutions. KD = kiln dried.

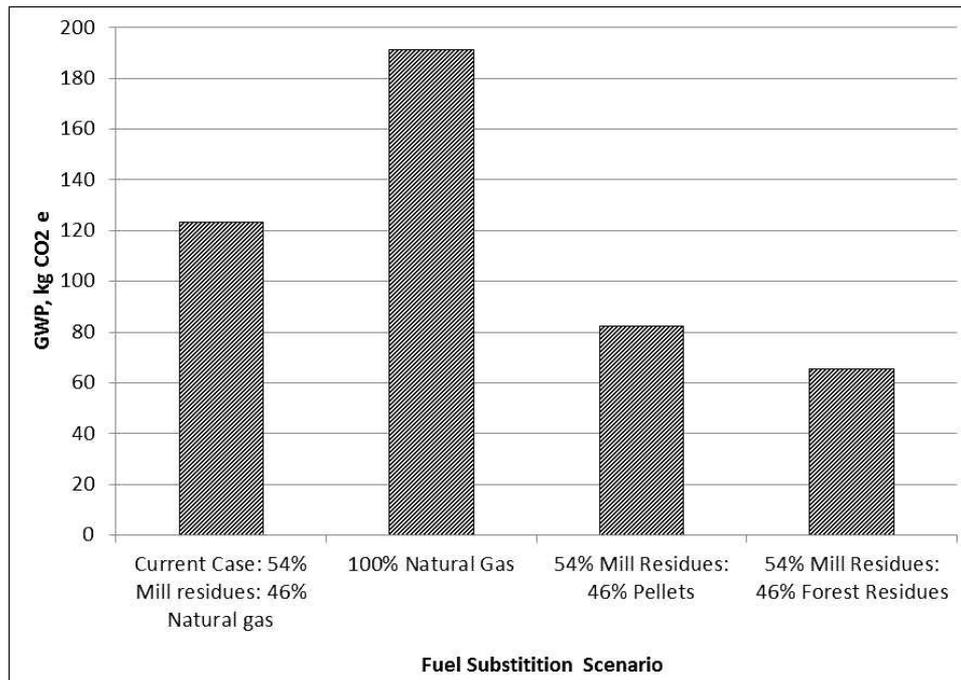


Figure 3.—Global warming potential (GWP) emissions from fossil fuels only, expressed in kilograms of carbon dioxide equivalents when producing 1 m³ Inland Northwest kiln-dried lumber under different boiler fuel scenarios.

Table 1.—Total and net global warming potential (GWP) in kilograms of carbon dioxide equivalents generated by biomass and fossil fuels combustion in boilers using different fuel sources.^a

Scenario	GWP (kg CO ₂ eq)			Net GWP (kg CO ₂ eq)
	Biomass	Fossil	Absorption (kg CO ₂)	
1. Current case, 54% mill residues:46% natural gas	94	124	-975	-757
2. 100% natural gas	1	191	-869	-677
3. 54% mill residues:46% pellets	223	84	-1,010	-703
4. 54% mill residues:46% forest residues	179	66	-1,064	-819

^a Boiler fuel input substitution per cubic meter of softwood kiln-dried, planed lumber.

If sustainably managed, biomass feedstocks remove from the atmosphere a quantity of CO₂ approximately equivalent to that released when the biomass is converted to fuel and burned for energy (US EPA 2006, Beauchemin and Tampier 2008, Fernholz et al. 2009). Hence, under sustainable management there is no additional carbon released into the environment when biomass is burned for heat or fuel production. The bioenergy produced more than offsets the fossil energy used, indicating more carbon is absorbed than released.

When biofuels are incorporated into a production process, there are many other processes that can contribute to carbon releases over the products' life cycle, such as the transportation of resources and raw materials, the production of electricity, and the production of other materials. The overall net kilograms of carbon dioxide equivalent emissions reported considers all emissions from all upstream processes (fossil and biogenic) and the carbon absorption prior to harvesting for the production of softwood lumber based on a mass basis of wood removed.

All carbon emissions, both biogenic and fossil based, released through each scenario are shown in Table 1. The total net GWP emission was highest for the pellet substitution (Scenario 3) as a result of the additional energy

requirement for their production. The total GWP was lowest for the 100 percent natural gas boiler fuel (Scenario 2), but this scenario produced the greatest amount of fossil fuel-based emissions. When using the EPA metric of reduced fossil carbon emissions as the objective, the current case (Scenario 1) resulted in 35 percent fewer emissions, the pellets case 56 percent fewer, and the forest residues case 66 percent fewer (Table 2).

When CO₂ absorption from and release to the atmosphere during tree growth are properly recognized as inputs and outputs, the net GWP is negative for all fuel-substitution scenarios, signifying that more CO₂ (both biogenic and fossil based) is removed than is released during the production of softwood lumber from cradle to gate (Table 1; Fig. 4). Because the values in Table 1 are referenced to a volume of lumber produced, CO₂ absorption not only includes the biofuel component, it also includes the mass of carbon represented in the 1 m³ of lumber.

The 100 percent natural gas fuel-input scenario used the least amount of wood, evidenced by the lowest CO₂ absorption: 869 kg CO₂ (Fig. 4). Even this scenario produced a negative net GWP because of the large influence of the carbon stored in the wood product, in terms of carbon mitigation. Net GWP was improved further when the use of

Table 2.—Ratios of carbon displaced to biogenic carbon released and total percent reduction in global warming potential emissions when biomass fuels displace fossil fuels in different boiler fuel scenarios in a softwood sawmill using two electricity generation scenarios.^a

Scenario	C_{net}/C_{wood}	Emission reduction (%)
Western electricity grid use at the mill		
1. Base case: 54% mill residues:46% natural gas vs. 100% natural gas	0.72	35
3. 54% mill residues:46% pellets vs. 100% natural gas	0.48	56
4. 54% mill residues:46% forest residues vs. 100% natural gas	0.70	66
With substitution for electricity at the mill		
5. Heat generation from 54% mill residues:46% natural gas and electricity generation from forest residues vs. heat generation from 100% natural gas with grid electricity generation	0.68	52
6. Heat generation from 100% natural gas and electricity generation from mill residues vs. heat generation from 100% natural gas with grid electricity generation	0.63	17

^a All scenarios use 100 percent natural gas for the comparisons.

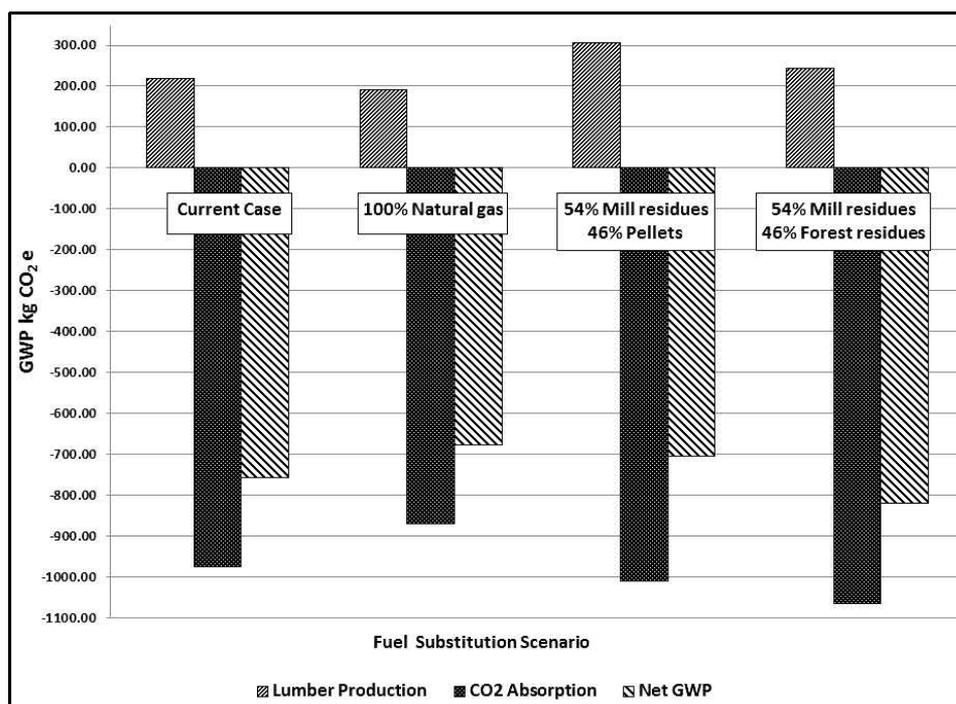


Figure 4.—Net global warming potential (GWP) emissions (biomass and fossil fuel based) expressed in kilograms of carbon dioxide equivalents when producing 1 m³ Inland Northwest kiln-dried lumber under different boiler fuel scenarios.

wood fuel was increased. Using forest residues for heat generation in the mill and reducing the use of natural gas produced the greatest benefit to net GWP over all scenarios, followed by the current case, and then pellets. Pellets produced the lowest emission reduction over the other biomass fuel scenarios because the feedstocks collected for pellets used so much fossil fuel. Pellets made from waste residuals that do not require as much fossil fuel would perform similarly to and perhaps better than forest residuals. Even when additional energy was required to produce the fuel, in the case of pellets, and carbon emissions were higher, this fuel still showed a reduction in net GWP from the carbon stored in products. As expected, using all natural gas for heat generation for lumber production produced the lowest benefit in net GWP because there was no absorption by biofuel to offset fossil fuel use.

Comparing the net carbon savings over fossil fuels for different biofuels provides insight into best options for wood

producers. When boiler inputs came from self-generated mill residues (54%), they embodied 94 kg CO₂ in the feedstock. This resulted in a 0.72-kg decline in fossil emissions for every 1 kg CO₂ in the wood (Table 2). Similar comparison showed that the production of ethanol to displace gasoline by gasification or fermentation resulted in only about a 0.38 reduction in fossil emissions for every 1 kg CO₂ in the wood (carbon net:carbon in wood; Lippke et al. 2012) or only about half the displacement efficiency gained from the mill residuals in a solid wood mill. From a pure efficiency measure of emission reduction per unit of wood produced, using woody biomass in the mill is substantially better than leaving it in the forest to decompose, burning it on site, or even using it to produce transportation fuel. The greatest emission reduction in our scenarios occurred when forest residuals were used for heat generation in the mill, which resulted in a 66 percent emission reduction over the 100 percent natural gas boiler

(Table 2). However, when biofuels are used to produce transportation fuels, even though the efficiency of reducing carbon emission per unit of wood used is low, it more directly contributes to reducing oil imports and the goal of energy independence. Energy independence contributes to the domestic economy and may be judged more important than reducing carbon emissions.

Table 2 summarizes the comparable efficiency metrics for the mill and the carbon tradeoffs for using biofuels for heat generation versus electricity generation. Neither electricity scenario (forest residues or mill residues) reduced emissions better than directly using forest residuals for heat generation. The results did show that using mill residuals for electricity production instead of for heat in the mill reduced carbon emissions by 17 percent compared with 35 percent. All scenarios showed that using the least amount of fossil fuels at the mill reduced net carbon emissions.

Conclusions

The greater use of woody biomass for heat energy reduced carbon emissions compared with fossil-based fuels. In all fuel-substitution scenarios, increasing the use of biomass for heat generation decreased GWP. Using woody biofuel for electricity production was somewhat less effective in lowering carbon emissions than when it was used for heat energy. But further investigation into forest residual collection methods, transportation distance, feedstock type, and moisture content, to name a few, could influence the biofuel impact. Heat generation at the mill under the current case of using about half self-generated mill residues and half natural gas resulted in a 35 percent reduction in GWP over heat production compared with using 100 percent natural gas. The greatest reduction in GWP compared with 100 percent natural gas (65%) resulted when forest residues were collected, chipped, and hauled to the mill for heat energy, eliminating the use of fossil fuel for drying.

Controversy exists over exactly how long wood (lumber) remains in service and the fate of wood after demolitions. Such controversies become more pronounced when the final disposal is landfilling and when heat recovery from the landfill is included. Although these fates of wood will have an additional impact on GWP, the level of this impact—whether positive or negative—remains uncertain, is outside the scope of this study, and does not alter the conclusions for the cradle-to-gate analysis. Further investigation into factors such as forest residual collection methods, transportation distance, feedstock type, and moisture content, to name a few, could help to better assess the impact of biofuels on carbon emissions.

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Cradle-to-Gate Life-Cycle Inventory and Impact Assessment of Wood Fuel Pellet Manufacturing from Hardwood Flooring Residues in the Southeastern United States*

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Abstract

In this article, we present cradle-to-gate life-cycle inventory (LCI) data for wood fuel pellets manufactured in the Southeast United States. We surveyed commercial pellet manufacturers in 2010, collecting annual production data for 2009. Weighted-average inputs to, and emissions from, the pelletization process were determined. The pellet making unit process was combined with existing LCI data from hardwood flooring residues production, and a life-cycle impact assessment was conducted using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) model. The potential bioenergy and embodied nonrenewable energy in 907 kg (1 ton, the functional unit of this study) of wood fuel pellets was also calculated. The pelletization of wood requires significant amounts of electrical energy (145 kWh/Mg), but the net bioenergy balance is positive. Wood pellets require 5.8 GJ of fossil energy to produce 17.3 GJ of bioenergy (a net balance of 10.4 GJ/Mg). However, if environmental burdens are allocated to the pellet raw material (flooring residues) by value, then the embodied fossil energy is reduced to 2.3 GJ. The pelletization unit process data collected here could be used in an assessment of the environmental impacts of pellet fuel, or when pellets are a pretreatment step in wood-based biorefinery processes.

The wood manufacturing industry in the United States obtains more than 50 percent of their heat energy requirements by burning wood residues produced during production (Puettmann and Wilson 2005, Puettmann et al. 2010). The primary sources for residential heating in the

United States are natural gas and electricity (US Energy Information Administration [US EIA] 2012), but firewood and wood residues are burned to supplement or even replace these energy sources in about 13 million homes. However, these wood fuels can be inconvenient to handle and store.

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Pelletization of wood residues can produce a more convenient fuel. Pellets are dry, dense, easily handled, and stable in long-term storage if kept dry. Pellets can be burned directly as a heating fuel, combined with other fuels such as coal, or can be an initial processing step in a biorefinery or biofuel conversion process (Magelli et al. 2009). Wood pellets are an established fuel product that is growing in importance in the United States and abroad, driven by rising fuel prices and demands for green energy sources.

Pellet fuel in the United States emerged as an alternative to oil in the 1970s after a sharp increase in oil prices. This was especially true in the Northeast, where pellets offered a convenient alternative for home heating. It was not until recently that the Southeast started seeing its own pellet industry developing. According to a report by the US Department of Agriculture (USDA) on North America's Wood Pellet Sector, the Southeast region of the United States produced just under 550,000 Mg (600,000 tons) of pellets in 2008 (Spelter and Toth 2009), about one-third of the North American total. Most of the southeastern pellet mills are components of other primary wood product facilities (i.e., hardwood flooring mills). Other, stand-alone pellet operations use the same waste material but from separate facilities. Pellet mills that use softwoods and/or roundwood (i.e., not processing residues) are not common in the US Southeast at this time.

While there have been several policy incentives to encourage new sources of bioenergy, such as the Biomass Crop Assistance Program (BCAP), it appears that the economic downturn of 2009 and 2010 has impeded the expansion of the pellet industry in the Southeast. Spelter and Toth (2009) listed 30 pellet manufacturers in the Southeast. Several of those facilities either temporarily halted production or entirely shut down as of the summer of 2010 (Pellet Fuels Institute [PFI] 2012). Despite this recent, local downturn, there is a longer term, global trend of significant expansion in the production and consumption of wood pellets (Spelter and Toth 2009).

There are a number of factors motivating the development of biofuels and bioproducts: high petroleum prices, a desire for energy independence, the need for rural economic diversification, and concern about the environmental impacts of using fossil carbon sources. With regard to the last point, intuition suggests that products and fuels made from plants inherently have environmental advantages. However, there is growing debate about these potential environmental benefits, and more attention is being paid to such matters as the amount of fossil carbon resources consumed in the production and processing of bioenergy and the potential tradeoffs (e.g., between food and fuel) involved. While the environmental advantages of biobased resources remain important, they can no longer be assumed—they must be demonstrated.

Life-cycle assessment (LCA) is an internationally accepted way to quantify the impacts and outputs of a product and the corresponding effects on the environment (Hunt et al. 1992, Curran 1996). The International Organization for Standardization (ISO) has published procedures for conducting LCA (ISO 2006). The life-cycle inventory (LCI) is one component of the LCA process and is an objective, data-based process of quantifying energy and raw material inputs and the emissions to air, water, and land. The life-cycle impact assessment (LCIA) characterizes and calculates the effects of the emissions identified in the LCI into

impact categories such as global warming potential, habitat modification, acidification, or noise pollution.

Outcomes from LCAs can be used to select more “environmentally friendly” products or to improve the environmental impacts of a particular product. An LCI for wood pellets would enable LCA-based comparisons of wood pellets and other fuels and would facilitate analysis of biorefinery operations that use pelletized wood, or other materials, within the process.

There have been a number of LCA studies of the production, transport, and use of pellets, often with LCIA comparisons to fossil fuel alternatives (Świgoń and Longauer 2005, Bradley 2006, Hagberg et al. 2009, Magelli et al. 2009, Sandilands et al. 2009, Fantozzi and Buratti 2010, Zhang et al. 2010, Sjlje and Solberg 2011, Uasuf and Becker 2011, Katers et al. 2012, Pa et al. 2012). None of these studies included the Southeast United States. In general, these studies found that using wood pellets for energy in place of fossil fuels results in reduced net fossil fuel-related emissions over their life cycle. However, these studies also highlight the importance of variables such as feedstock moisture content and processing energy inputs and sources. Because of the potential for different LCA results from different areas, and because the Southeast is the single largest and fastest-growing region for wood pellet production in the United States (Spelter and Toth 2009), an LCI specific to the US Southeast pellet industry is needed.

Goal

The goal of this study was to document the cradle-to-gate LCI of manufacturing bagged wood pellets based on hardwood resources from the Southeast US pellet-manufacturing region. The output of this study is intended for use by researchers and practitioners as an input to the LCA of woody biomass materials in a cradle-to-gate analysis. This study measured only the impacts associated with the production of pellets from hardwood flooring residues. The primary data were collected by a survey of pellet manufacturers. This survey questionnaire is located at <http://www.renewablecarbon.org/PDF/survey.pdf>. Secondary data included electricity rates (to determine electricity consumption by individual pellet mills when electricity expense was reported) as reported by the US EIA (2012) and hardwood flooring residues production from the US LCI database (Hubbard and Bowe 2010).

Scope

The LCI study surveyed the use of dry hardwood flooring residues for bagged pellet production in the Southeast region of the United States (pellet mill gate-to-pellet mill gate). Product transportation was beyond the scope of the study. Because wood flooring residue-based operations are currently predominant in this region, these were the mills surveyed. It could be that softwood and/or hardwood roundwood-based operations will be important in the future and that the environmental impacts of their pellets will be different; however, these potential differences are outside the scope of this study.

Methods

To conduct the survey of wood pellet manufacturers, all of the pellet mills (24 mills for the Southeast region in operation at the time of survey) were contacted and sent an

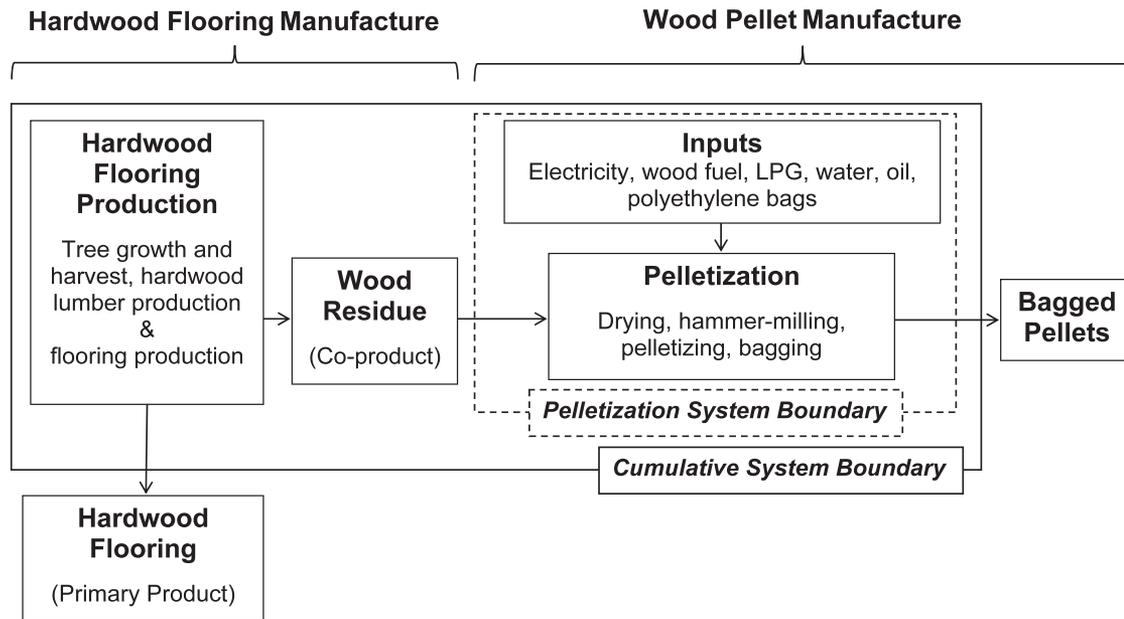


Figure 1.—Components of the wood pelletization process.

LCI survey from October to December 2009. Of the mills surveyed, six (25%) responded with complete data in terms of pellet production, raw materials, electricity, and fuel use. Respondents were obtained from mills in Alabama, Kentucky, Tennessee, Virginia, and West Virginia. Surveyed LCI data represented 2009 production data. The survey served as the main tool for the inventory (LCI) collection (gate-to-gate). SimaPro LCA modeling software (PRé Consultants 2012) was used to calculate the overall cradle-to-gate emissions associated with the pelletization process using a network of related inventories associated with the inputs for pellets. These inventories included LCI data for hardwood flooring residues production (Hubbard and Bove 2010) and for electricity production (USDA 2012). Impact indicators were calculated using the tool for the reduction and assessment of chemical and other environmental impacts (TRACI 2, v. 3.03) model (US Environmental Protection Agency [US EPA] 2011).

The manufacture of wood pellets comprises the following processes: raw material (wood waste) collection, drying, hammer milling, pelletizing, cooling, and bagging. The inputs are wood waste from wood flooring manufacturing (sawdust, trimming, scraps, etc.), energy (electricity and fuel), lubricants (corn oil and grease), and water. The output is bagged wood fuel pellets. Any wood residues generated during pellet production are recycled in the system. Pellets generated by the companies surveyed in this study generally meet the “premium” standard of the Pellet Fuels Institute (PFI 2010).

Unit process and system boundary

The unit processes described in Figure 1 are within the system boundary for the cradle-to-gate LCI analysis of wood pellet manufacturing (“pelletization”). The dotted and solid lines cover pelletization and cumulative emissions, respectively. The pelletization system boundary covered the cradle-to-gate emissions, including emissions generated for material and energy produced off-site, such as grid electricity that is used on-site, but excludes cradle-to-gate

emissions for wood residue production. Life-cycle data for wood residue production were provided on a mass allocation basis. About 50 percent of wood leaving the wood flooring manufacturing process was wood residue; therefore, the wood residue carries 50 percent of the burden from the wood flooring manufacturing process. Cumulative emissions (the solid line) cover the cradle-to-gate emissions generated for material and energy produced for both wood residue and pelletization production. The functional unit was 907 kg (1 ton) of bagged wood fuel pellets, which is the standard unit in commerce. The following describes each of the manufacturing processes.

1. Raw material (waste) collection: Raw material is collected on-site from a connected but separate wood processing facility such as a hardwood flooring mill. Approximately half of the hardwood lumber raw material is converted to flooring; the remainder (sawdust, planer shavings, trim blocks, and edging strips) is available for the pellet process. The raw material is stored in a dry facility on-site.
2. Drying: Raw materials, when taken from green feedstock (i.e., roundwood), must be uniformly dried to a low moisture content (9% to 11% on an oven-dry basis). The mills surveyed for this study all use waste residue from adjoining facilities, which already has a low moisture content level; however, additional drying is sometimes used even for dry residues. One facility in this study did use a gas boiler, which significantly impacted their energy input. One other facility used wood waste (sawdust) to dry 80 percent of their raw material. Weighted averages of both of these facilities’ inputs were used in the inventory analysis.
3. Hammer mill: Once the material is collected, it is broken down into small, uniform particles (~2 mm) using a hammer mill. The hammer mill is operated by electric motors.
4. Pelletizer: Pellets (~6 mm in diameter and 25 mm long) are extruded using machinery that is similar to the

equipment used to form feed pellets for the agriculture industry. Pelletizers use large electric motors to extrude the pellets through steel dies. High pressure (~300 MPa) and temperatures (~90°C) soften lignin and binds the wood particles together to make uniform and consistent pellets. While no adhesives are required for this process, small amounts of lubricants and water are sometimes added to improve processing.

5. Cooling: The pellets are hot when they emerge from the pelletizer, and they enter a counterflow cooler to expedite cooling and evaporation. Then they are stored in a hopper and further cooled before bagging.
6. Bagging: Finished pellets are bagged, usually in small, semiautomated bagging lines that are powered by electricity. Pellets are usually fed by conveyor to a bagging station where the pellets are fed into 18.14-kg (40-lb) plastic bags.

Because we were unable to collect data for each component of the pelletization process, this LCI does not separate inputs and outputs by unit processes; instead, data were collected on the processing of wood pellets as a whole system from gate (wood residue) to gate (bagged pellet).

Assumptions

The data collection, analysis, and assumptions followed the protocol defined in Consortium for Research on Renewable Industrial Materials (CORRIM) “Research Guidelines for Life Cycle Inventories” (CORRIM 2010). Additional conditions include the following:

- All data from the survey were weight averaged for the six plants based on each mill’s pellet production for 1 year (2009). Missing data were not included in the weighted averages.
- The electricity consumption (the largest input of this manufacturing process) is expressed as kilowatt hours per ton of pellets using electricity data taken from the US LCI database (USDA 2012). Most pellet manufacturers reported electricity bills that allowed us to calculate the energy (kWh) based on their production rate. One mill reported actual kilowatt hour usage.
- Only two mills reported values for oil and grease as inputs. These amounts were calculated per ton of wood pellets. The weighted average for these two reporting manufacturers assumed that the other manufacturers used similar amounts of oil and grease as lubricants.
- Only one mill reported a value for liquid petroleum gas (LPG), 5.71 liters/Mg of wood pellets (1.37 gal/ton). This mill used LPG for further drying before pelletization. This input was weighted according to production percentages.
- Two mills reported values and gave samples of bags used for the finished pellets. It was assumed that these bags were representative of bags used at all of the mills.
- One mill reported using 80 percent green wood feedstock. The mill used heat from burning wood residues to dry the feedstock, and this wood input was weighted according to production percentages and included.
- Environmental impacts associated with the pellet mill equipment and any replacement parts were not included.

LCIAs were performed using TRACI 2 (US EPA 2011). TRACI is a midpoint oriented LCIA methodology developed by the US EPA specifically for the United States using input parameters consistent with US locations. The

environmental midpoint impact categories of global warming potential (kg CO₂ eq), acidification potential (H⁺ moles eq), respiratory effects (PM 2.5 eq), eutrophication potential (kg N eq), and smog potential (kg NO_x eq) were examined.

Results

Six (25%) of 24 mills responded to the survey. The size of the production facilities that responded to the survey ranged from 5,440 to 113,000 Mg (6,000 to 125,000 tons) of wood pellets annually. Most of these facilities were colocated with hardwood floor manufacturers, and all used hardwood flooring residues for their raw material. Pellet facilities ranged widely in operation times and employees. Some facilities were 24-hour, 7 days a week operations, while many of them were run for 5 days a week at 8 hours a day.

The total production of responding pellet mills was 303,912 Mg (335,074 tons) of pellets for 2009. The only available production data estimated that production of the entire Southeast region in 2008 was 537,000 Mg (592,000 tons; Spelter and Toth 2009), which suggests that our survey captured production information from mills that produce about half of the total regional production, assuming there were no major shifts in production from 2008 to 2009.

The reported data are consistent with pelletization energy consumption values reported in other studies (Thek and Obernberger 2004, Mani 2005, Hagberg et al. 2009, Zhang et al. 2010, Sjlje and Solberg 2011, Katers et al. 2012, Pa et al. 2012). The procedures and report of this study follow the standards in ISO 14040 (ISO 2006). The procedures and report also follow the research guidelines for LCIs used by other researchers in the CORRIM group (CORRIM 2010).

Material flows

The most significant inputs for pellet operations are wood residues and electricity. The surveyed manufacturers reported no cogeneration of electricity. Other fuels used are primarily for rolling stock (i.e., forklifts) and include diesel fuel and LPG. This machinery was usually shared between the pelletization plant and other components of the hardwood flooring operation. The survey respondents were unable to report a fuel usage for these machines specifically for the pelletization operation. Given the limited requirements for these machines in the pellet making process, these inputs were assumed to be insignificant. Other material inputs used in the manufacture of wood pellets are plastic bagging, water, oil, and grease. Water is used to adjust the

Table 1.—Inputs to the pelletization process for 1 ton of wood pellets in the Southeast.

Input	Quantity
Materials	
Wood residues (kg)	907
Polyethylene (50-kg bags)	5.01
Corn oil lubricant (liters)	1.25
Water	
Ground water (liters)	21.70
Energy	
Electricity (kWh)	132.12
Liquefied petroleum gas (liters)	0.08
Wood residues to boiler (kg)	29.97

Table 2.—Emissions to air, water, and soil associated with the production of 1 ton of bagged wood pellets from hardwood flooring residues.

Emissions	Wood residues production, cradle to gate (kg)	Pelletization (kg)	Cumulative wood residues production and pelletization (kg)
Air emissions			
CO ₂ (fossil)	203	114	317
CO ₂ (biomass)	457	65	522
Acetaldehyde	0.002	0.000	0.002
Acrolein	0.009	0.001	0.010
Formaldehyde	0.01	0.109	0.119
Phenol	0.000	0.000	0.000
NO _x	1.67	0.41	2.08
SO ₂	0.96	0.85	1.81
SO _x	0.156	0.043	0.199
Methane	0.485	0.329	0.814
Particulates (unspecified)	1.44	0.12	1.56
Volatile organic compounds	1.66	0.06	1.72
Water emissions			
Biological oxygen demand	4.56	0.64	5.20
Suspended solids	0.296	0.081	0.377
Chemical oxygen demand	0.053	0.021	0.074
Chloride	5.93	2.15	8.08
Soil emissions			
Wood ash	0	0.21	0.21

moisture content during pelletizing. Some oil and grease are used for lubrication in the pelletizing process.

The process of pelletizing wood waste changes only the density of the wood residue raw material. Therefore, it takes 1 ton of wood residues to produce 1 ton of wood pellets. The manufacturing inputs determined from the surveys are summarized in Table 1.

Life-cycle inventory

Wood pelletization primarily has energy and wood residue inputs and only one output—wood pellets. Electricity is used to operate almost all the systems, as described in the next section. Wood pelletization does not create a solid waste stream.¹ All wood residues are recycled in the pelletization process, and airborne particulate emissions (dust) are assumed to be insignificant. Because air, water, and solid waste emissions are minimal, the majority of emissions (Table 2) are those associated with pregate actions (hardwood flooring manufacture and electricity production).

The cumulative life-cycle emissions and wastes associated with wood pelletization are pregate (i.e., those associated with wood flooring production and electricity production). There are no emission control measures used during pelletization.

Table 2 lists the emissions to air, water, and soil for wood residues production (cradle to gate), for the pelletizing

process (gate to gate), and for these two processes combined (cumulative). The data collected by our survey for the pelletizing process are listed under the heading “pelletization” in the table. The cumulative emissions include those associated with the growth, harvest, and transportation of logs and the production of the hardwood flooring that results in the creation of wood residue, and the emissions associated with the production of the electricity (calculated in SimaPro from data provided by Hubbard and Bowe [2010] and the US LCI database [USDA 2012]) that is used during pelletization. Separation of the wood residue production, pelletization, and cumulative impacts in this way enables analysis of the relative importance of the pelletizing process compared with raw materials (wood residues) production. Pelletization-associated fossil CO₂ emission of 125 kg/Mg includes emissions from generation of the electricity used to run the pelletizing equipment and burning LPG to dry the wood residue. In addition, woody biomass is burned on-site for drying the wood residue as shown by a biomass CO₂ value of 72 kg/Mg. Most of the fossil and biomass CO₂ emissions are associated with the hardwood flooring residues production.

Impact assessment

The various impact categories for the production of wood pellets, showing each input’s relative contribution, are shown in Figure 2. The largest impact for each category is carried over from the wood residue material (i.e., tree growth, wood harvest, transportation, and wood flooring manufacture). However, the additional input of electricity for pelletization has an important impact on most categories. The plastic bag used to store the pellets also has a noticeable impact in some categories, e.g., respiratory effects. Other inputs used in the pellet-making process, such as the oil for lubrication, had negligible impacts.

Wood pellets are a potential source of convenient renewable biomass energy, but some nonrenewable energy (i.e., electricity derived from coal, etc.) is required to make the wood residues and to transform the residues into the more convenient pellet fuel. Figure 3 depicts the relationship between total potential biomass energy in the pellets and the associated cradle-to-gate fossil fuel emissions related to producing wood residues and manufacturing pellets. Burdens assigned to the wood residues coproduct are allocated by mass (left) or by value (right) relative to the primary wood flooring product. Wood pellets can provide a net benefit in terms of providing biomass energy, but their embodied fossil energy is important. Wood pellets require up to 5.8 MJ of fossil energy to produce 17.3 MJ of bioenergy for a net balance of 10.4 MJ/Mg.

Wood processing residues are generated as a coproduct from manufacturing hardwood flooring. Because the residues’ impacts are allocated *by mass* (a 50%:50% split) from the production of hardwood flooring, pellets are assumed to carry significant environmental impacts (see Fig. 3, left). A change in allocation procedure for wood flooring manufacturing would affect the conclusions considerably (Kim et al. 2009, Luo et al. 2009) because wood residues are of low value compared with the primary product (i.e., hardwood flooring). The total cradle-to-gate cumulative allocated energy (i.e., fossil energy and bioenergy) required to make a wood pellet is 13.4 MJ/Mg, based on mass-based allocation of embodied energy to the wood residues produced during hardwood flooring manufacture. If value-

¹ This is true except for wood ash in cases where wood residues are dried using a wood-fired boiler estimated at 0.75 percent of incoming oven-dried wood fuel (Koch 1985). As noted in the “Assumptions” section, there was one producer that dried using a wood-fired boiler, but they were unable to report an ash value.

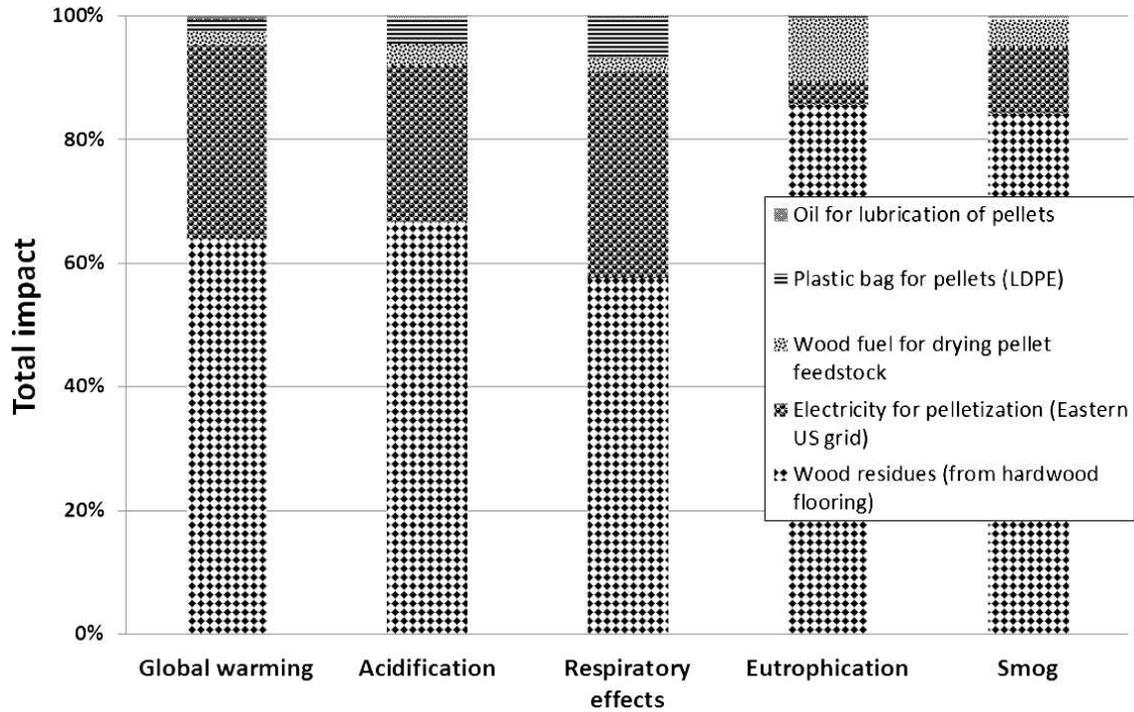


Figure 2.—Impact categories showing relative contribution of the inputs.

based allocation is used, the total embodied energy (fossil energy and bioenergy) for a ton of wood pellets is reduced to 3.0 MJ/Mg. Biomass energy (i.e., wood combustion energy) makes up about 53 and 12 percent of the total embodied energy in mass- and value-based allocation scenarios, respectively.

For wood flooring manufacturing, if allocation were done by economic value instead of mass, the burdens assigned to the (low-value) wood residues would be reduced. For example, if we assume that wood flooring has a wholesale

value of \$2/ft² (\$1,764/Mg) and that wood residues have a value of \$20/ton (\$22/Mg; at the mill gate), then the allocation of burdens would be 98.8 percent to the flooring product and 1.2 percent to the residues. In that scenario, the fossil energy associated with producing the residues would be reduced from 3.4 to 0.08 GJ (Fig. 3, right). If the wood flooring residues were assumed to have no environmental impacts associated with them (i.e., the burdens were allocated entirely to the flooring), then only the *additional* inputs required to convert the hardwood flooring residues to

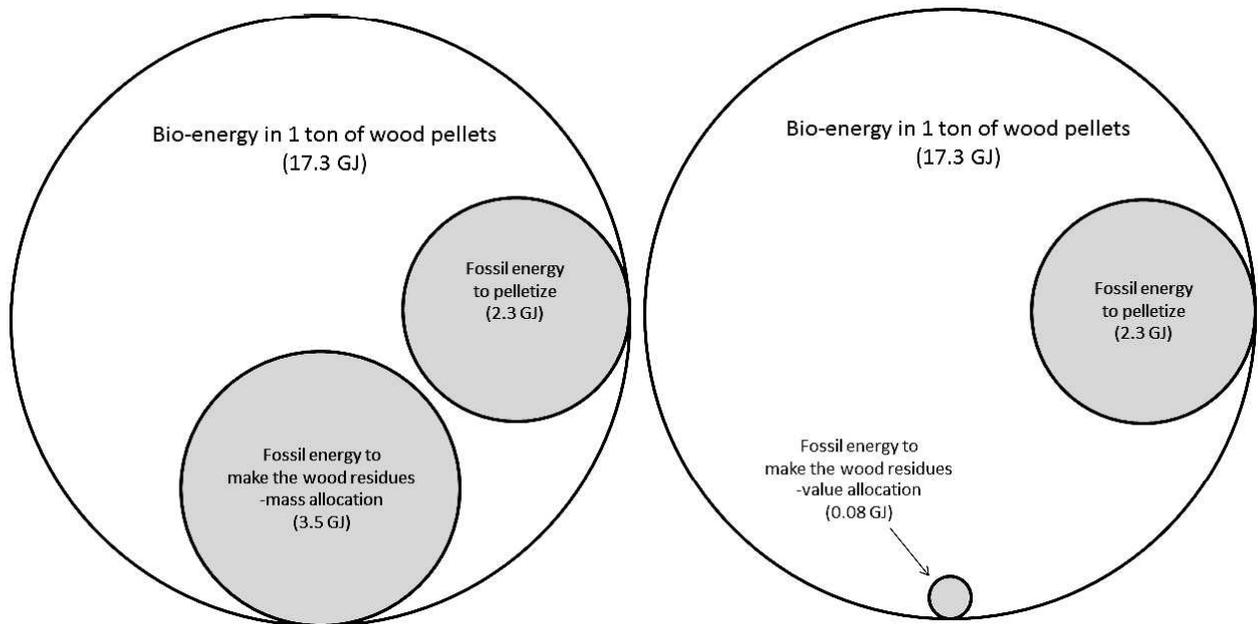


Figure 3.—Potential and embodied energy in 1 ton of pellet fuel by mass (left) and by value (right).

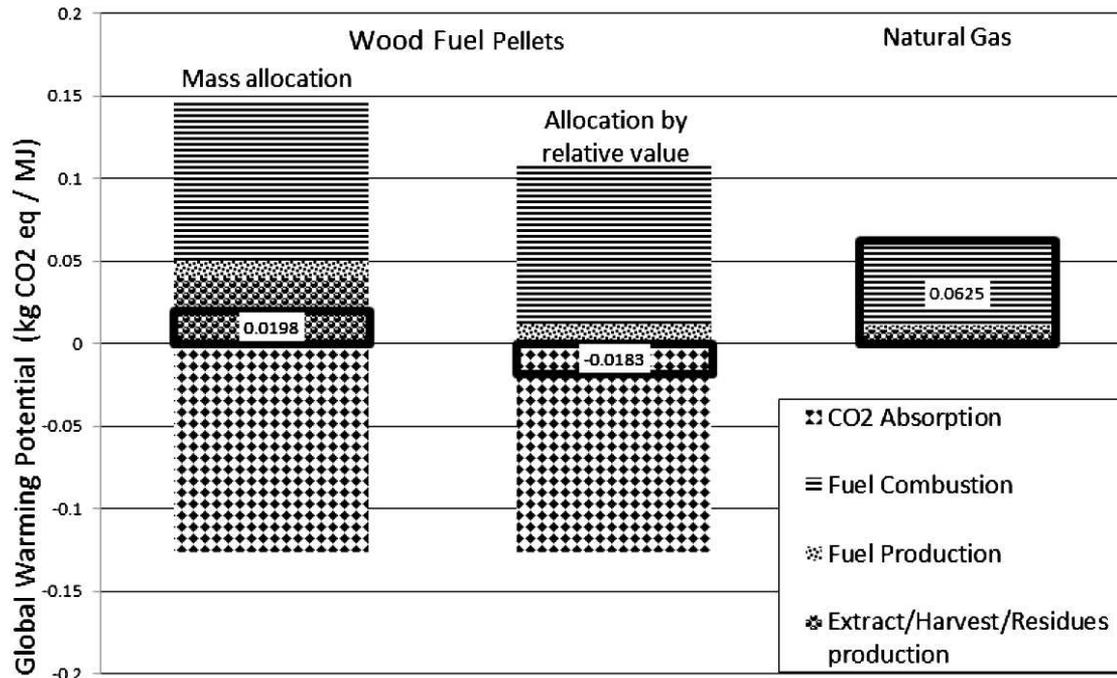


Figure 4.—Global warming potential of wood pellets and natural gas.

pellets would be considered, and only the pelletization-specific inputs and emissions described above would apply to the pellet product. Allocating all the burdens to the wood flooring would be consistent with the premise that wood flooring manufacturers are in the business to make flooring not wood residue. However, because there is (relatively small) economic value in wood residues, economic allocation may be the most appropriate method (Jungmeier et al. 2002, Luo et al. 2009, FPInnovations 2011).

Because the amount of nonrenewable energy used to produce pellets is less than the potential bioenergy they contain (Fig. 3), the global warming potential (GWP) of pellet fuel is much less than fossil fuels such as natural gas (Fig. 4). This comparison to natural gas is intended to provide a baseline analysis. Transportation of the fuels to the combustion was not considered for this analysis and combustion efficiencies of 83 and 80 percent were assumed for pellets and natural gas, respectively (Forest Products Laboratory 2004). Transportation of pellets can have a major impact on their energy balance, as shown by Magelli et al. (2009); however, an LCA that included transportation was beyond the scope of this study.

Allocation of the burdens (i.e., fossil energy inputs) from wood residues production is again an important variable in the analysis. If embodied fossil energy inputs are allocated to the hardwood flooring residues by mass, then the GWP of pellets is less than half that of gas; however, if the residues are considered to be a low-value coproduct, then the GWP of pellet fuel becomes negative. If the wood flooring residues are simply considered a waste and are assumed to carry no embodied fossil energy, the GWP calculation becomes even more favorable (data not shown); however, the additional apparent benefit is minor given the assumed low monetary value of the wood residues (1.2% of the total value).

Limitations

As with all LCIs and LCAs, the conclusions that can be drawn are influenced and constrained by the underlying assumptions. This study focused on a particular type of pellet operation (operations that use hardwood flooring residues) in a particular location (the US Southeast). Results for mills that use other resources—particularly those that require additional drying as part of the pellet-making process—will be dramatically different (Hagberg et al. 2009). The additional production that is forecast for the pellet industry globally may well involve roundwood (nonresidue) raw materials. The results for this study were also heavily influenced by the local electrical generation source. For example, locations that rely on hydropower for electrical generation (Sjlie and Solberg 2011) will produce different GWP results from those calculated here.

This study included a cradle-to-gate analysis, but environmental impacts beyond the mill gate could be important, for example when transportation to markets in Europe is considered (Magelli et al. 2009). However, this study can provide a building block for such “cradle-to-grave” analyses.

Only 25 percent of the mills in the region responded to the survey (representing about 50% of the production). The data collected from these mills may not be more broadly representative; however, as noted above, the electrical energy and other inputs were consistent with other reports.

Conclusions

This study presents a cradle-to-gate LCI and LCIA for the production of wood fuel pellets in the Southeast region of the United States. Operating mills were surveyed to collect data for a gate-to-gate life-cycle inventory. The six responding mills generally used hardwood flooring residues as raw material. Drying requirements for the feedstock were minimal. A cradle-to-gate inventory was developed using

existing life-cycle data for wood residues, electricity, and the other inputs. The primary inputs for manufacturing wood fuel pellets are wood residues and electricity. In the Southeast region, a weighted average of 132 kWh of electricity was reported for the pelletization of 1 ton (907 kg) of wood residues. This represents an energy input within the range of other reported values for pellets produced from dry feedstocks (Thek and Obernberger 2004, Mani 2005, Hagberg et al. 2009, Zhang et al. 2010, Sjlje and Solberg 2011, Katers et al. 2012, Pa et al. 2012).

The LCI data from this study represent actual reported mill production values and could be a useful component of LCAs of wood operations that use pellets as a fuel or intermediate product. However, raw material variations, especially when feedstocks require drying before pelletization, should be carefully considered when attempting to apply these data to other circumstances. Likewise, the greenhouse gas (GHG) impact of the Eastern United States coal-based electrical supply to the pellet mill was important in this study; regional variations in electrical energy generation could affect the conclusions for pellets produced in other locations (e.g., hydropower as in Sjlje and Solberg 2011).

LCIA allows for the interpretation of several impact categories, such as global warming potential (weighted net emissions of GHG), acidification, carcinogenics, respiratory effects, and eutrophication. If we apply the mass allocation procedure for wood flooring manufacturing (Pa et al. 2012), the production of wood residues from hardwood lumber manufacture contributes the most to the total environmental impacts of wood pellet products. The electricity required during pelletization also contributes significantly, e.g., 30 percent of the GWP and the total respiratory effects are associated with this input. The plastic bag used for bagging pellets represents a smaller, but still significant, impact in some categories.

Comparison of the biomass energy in pellets with the significant fossil energy inputs required for their production shows that wood pellets provide a net renewable energy source. Net energy available in wood pellets is 10.4 MJ/Mg or more. Analysis of the energy balance and environmental impacts of pellets is greatly affected by the allocation method used. The appropriate allocation method when the residual coproduct is of lower value than the primary product, as is the case for hardwood flooring residues, would be a value allocation by which the primary product carries almost the full burden up until the waste is used as a feedstock for the production of pellets (FPInnovations 2011). The fossil emission reductions when combusting pellets compared with natural gas varies from 123 percent reduction when the flooring burdens are allocated to the pellets based on their relative value to 56 percent when mass allocation is assumed.

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