# 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, Sjlie 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

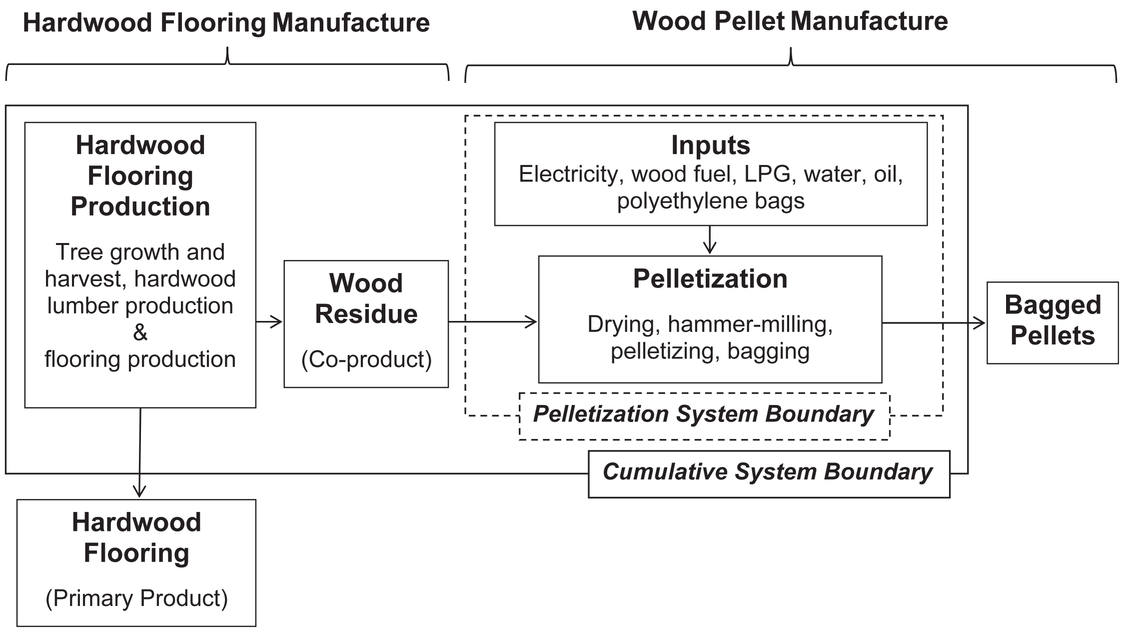


*Figure 1.—Components of the wood pelletization process.*

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 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 Bowe 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 ovendry 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 $CO_2$ 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, Sjlie 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 $CO_2$ 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 $CO_2$ value of 72 kg/Mg. Most of the fossil and biomass $CO_2$ 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 ovendried 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.

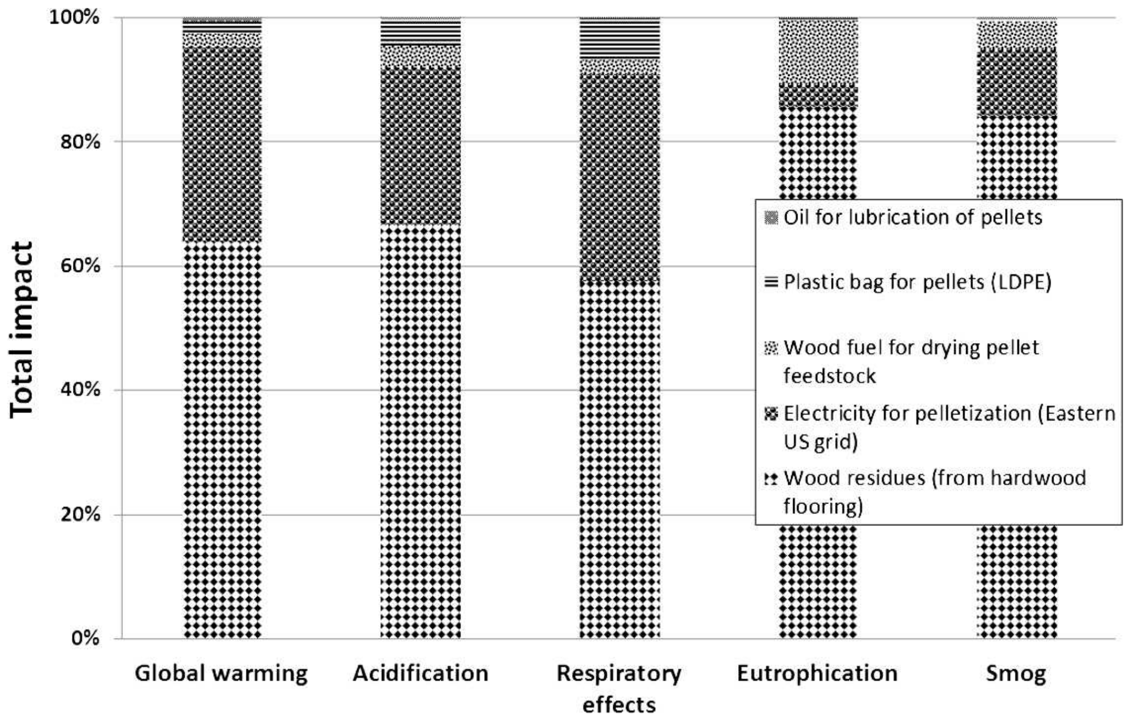


*Figure 2.—Impact categories showing relative contribution of the inputs.*

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 $2/ft$^2$ ($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

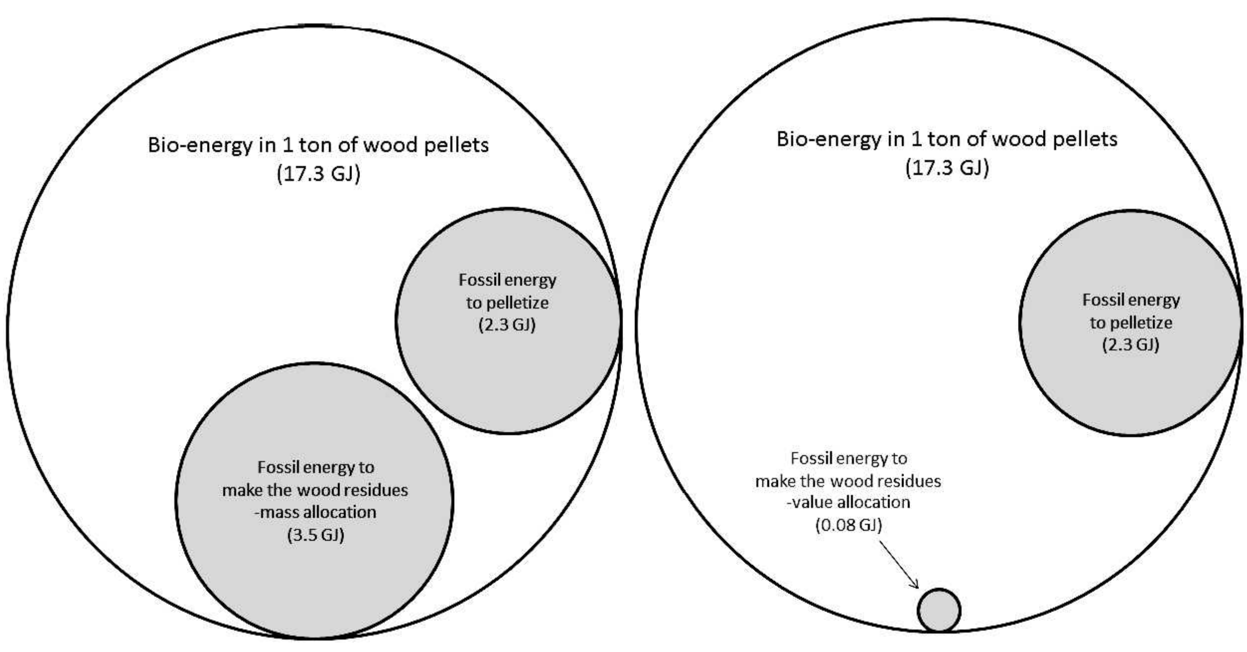


*Figure 3.—Potential and embodied energy in 1 ton of pellet fuel by mass (left) and by value (right).*

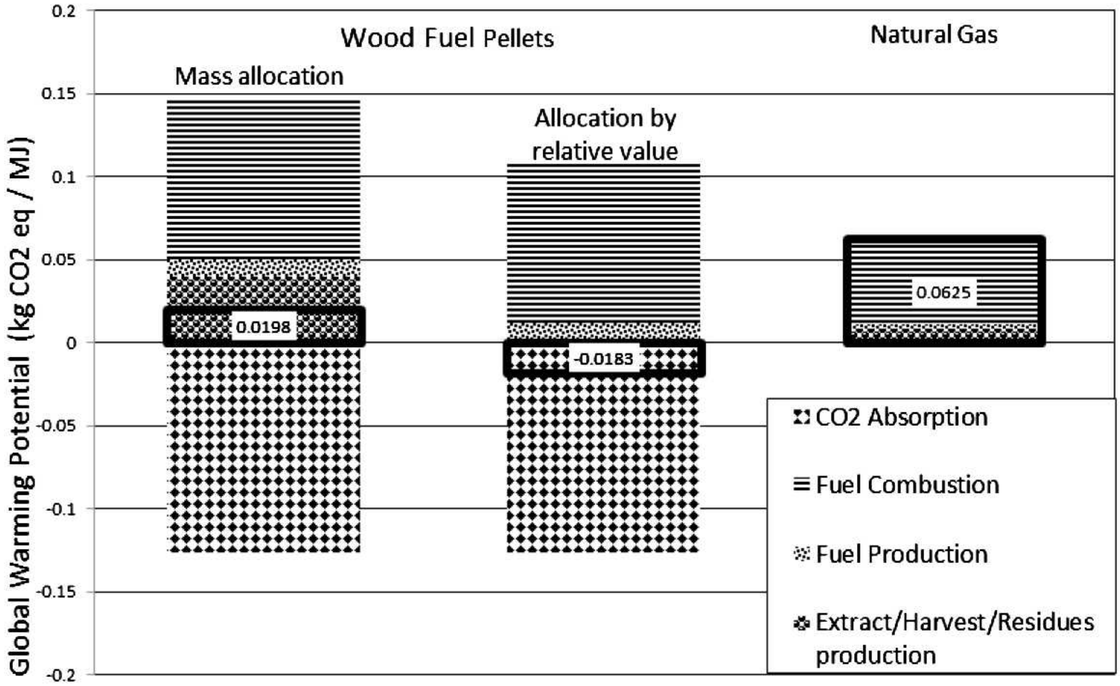


*Figure 4.—Global warming potential of wood pellets and natural gas.*

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, Sjlie 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 Sjlie 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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