Evaluation of the Energy Balance for the Production of Briquettes from Biomass

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Abstract

Wood densification consists of processing wood by-products such as sawdust and chips into uniformly sized particles that are compressed into wood-based fuel products (pellets and briquettes). The main advantages are related to handling improvements of residual wood and energy generation opportunities when compared with wood chips from other forms of wood residues. The objective of this study was to evaluate the energy balance for production of briquettes from wood residues.

This research involved determining the energy consumption required to perform the main manufacturing operations to produce wood briquettes: size reduction, drying, and densification of wood. The amount of energy that can be obtained from the combustion of wood briquettes was also measured. The effects of several factors such as wood species, material dimensions, and raw material moisture content on the energy requirements for manufacturing briquettes were studied.

Four densification strategies were evaluated from an energy consumption standpoint: single size reduction (shredding) of dry lumber and wood chip densification; single size reduction (shredding) of wet lumber, drying, and wood chip densification; double size reduction (shredding and hammermilling) of dry lumber and wood particle densification; and primary size reduction (shredding) of wet lumber, wood chip drying, secondary size reduction of wood chips, and wood particle densification. At most 8 percent of total energy available from combustion of briquettes is required to produce briquettes. Moreover, drying wet wood residues consumes about 80 percent of the energy used in producing the briquettes.

This study shows that manufacturing briquettes from wood residues is feasible from an energy consumption perspective.

Densification of wood is a multi-operation manufacturing process (Fig. 1). In general, the raw material has to fulfill specific properties such as size, uniformity, and moisture content before being densified; thus the raw material needs to be preprocessed. This preprocessing stage includes size reduction operations (comminuting, milling, grinding, chipping, etc.) and drying operations. Once the raw material is prepared, it is compressed under high temperature and pressure conditions. This last step is the densification stage, which results in the final products (briquettes or pellets). It is important to note that wood densification is simply a physical transformation that does not change the chemical composition of wood (Tabarés et al. 2000).

The process of transforming wood residues into compressed fuel (pellets and briquettes) requires large amounts of energy. Some studies have focused on analyzing the energy efficiency of converting wood residues into densified products, especially pellets. For instance, Reed and Bryant (1978) stated that the energy requirements for densification vary between 0.032 and 0.08 MJ/kg (44 to 110 BTU/lb), which is about 0.5 to 1 percent of the energy in biomass. However, since biomass typically has to undergo several processes such as separation, drying, and size reduction prior to densification, overall energy requirements reach 5 to 15 percent of the energy in the raw biomass (Reed and Bryant 1978). Resch (1982) estimated that once the wood

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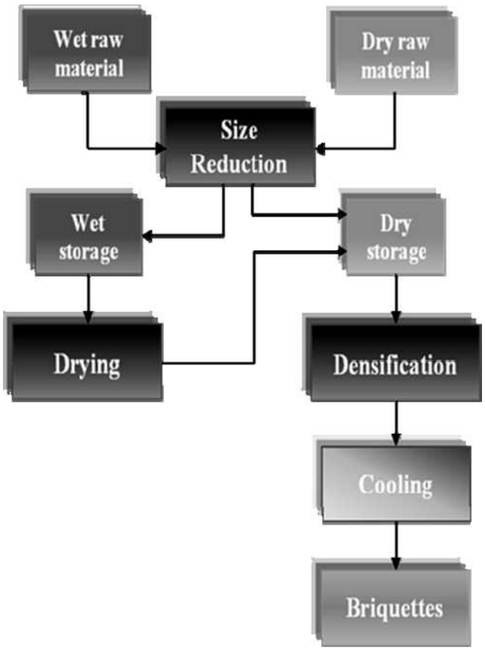

Figure 1.—Flow diagram of a densification process for production of briquettes (adapted from Hassler et al. 1990).

fuel is dried, energy requirements for densification usually range between 0.12 and 0.44 MJ/kg depending on the equipment and wood species.

Based on studies by Wach and Kołacz (2003) and Pasyniuk (2004), cited by Świgoń and Longauer (2005) the electrical consumption of milling, drying, and densification for production of pellets is about 0.144 MJ/kg (40 kW·h), 0.288 MJ/kg (80 kW·h), and 0.072 MJ/kg (20 kW·h), respectively.

As cited in Patzek and Pimentel (2005), Nielsen and Estcourt (2003) analyzed an example in which a very inefficient plant spent approximately 16 MJ/kg to transform low quality wood waste into pellets—roughly 80 percent of the calorific content of ovendry hardwood.

The European Biomass Industry Association (2007) reported that the energy demand for production of wood pellets depends on the initial particle size, moisture content, technology used, and plant scale. According to this association, the energy consumption to produce wood pellets is about 4.1 MJ/kg (1,140 kW·h per ton of pellets), which can mainly be broken down into 0.29 to 0.54 MJ/kg (80 to 150 kW·h per ton) for electricity and about 3.42 MJ of heat per kg (950 kW·h of heat per ton) of water to be vaporized.

Thek (2004) found that when wet raw material was used and drying was necessary, specific electricity consumption roughly varied between 0.46 and 0.58 MJ/kg (128 and 160 kW·h per ton) of pellets depending on the scenario being analyzed. On the other hand, when dry raw material was used—no drying included in the production line—the specific electricity consumption ranged from about 0.27 to 0.47 MJ/kg (75 to 130 kW·h per ton) of pellets.

Nonetheless, there is still a lack of information with respect to the energy efficiency process of transforming wood residues into densified products as well as the energy that may be obtained from the combustion of these products, specifically briquettes. Therefore, this research project was intended to study in detail the energy consumption along the whole densification process of residual wood for the production of briquettes.

Materials and Methods

Size reduction

Shredding.—Three factors constituted this part of the experiment: wood species, initial condition of the raw material (lumber) for primary size reduction (shredding), and particle size obtained from primary size reduction. Three wood species were considered: eastern white pine (*Pinus strobus*), southern yellow pine (*Pinus taeda*), and yellow poplar (*Liriodendron tulipifera*). The initial condition of the raw material (lumber) for primary size reduction was analyzed at two levels: green lumber (from a local sawmill) and kiln-dried lumber (from a local supplier). The particle size of the material obtained from primary size reduction (shredding) was studied at two levels: wood chips from 12 to 15 mm in size and those from 15 to 20 mm in size. Three replicates for each treatment were tested, and the average of these replicates was used as a final result. The response parameter evaluated in this part of the experimental design was energy consumption for shredding wood.

Moisture content of the lumber was determined using an RDM-2 pin-type moisture meter (Delmorst Instrument Company). Three moisture content measurements were taken lengthwise to calculate the average moisture content of the board.

The equipment used for size reduction of wood depended on the initial properties of the material and the desired size of the final material. A Weima Tiger 400 horizontal shredder was used for size reduction of green and kiln-dried pieces of lumber (19 by 38 by 1219 mm) into wood chips of 12 to 15 mm or 15 to 20 mm. Pieces of lumber were individually placed on the shredder's vibrating conveyor so that the cutting knives on the shredding rotor were symmetrically distributed along the width of the lumber pieces. This comminution operation was called primary size reduction.

Hammermilling.—As with wood shredding, three factors were also analyzed in this part of the experiment: wood species, initial condition of the raw material (lumber) before primary size reduction (shredding), and chip size. Three replicates for each treatment were tested, and the average of these replicates was used as a final result. The response parameter evaluated in this part of the experimental design was energy consumption for hammermilling wood.

A C.S. Bell Company 10HBML rotary hammermill was used to reduce the size of chips obtained from the horizontal shredder into 3-mm particles. Chips were gradually dropped in the hammermill's chute, and gravity and vibration conveyed the chips into the milling chamber. Since the hammermill could only process dry material, as recommended by the manufacturer, chips obtained from shredding green lumber were air dried prior to size reduction in the hammermill. This comminution process was labeled as secondary size reduction.

Drying

Wood chips obtained from size reduction of green lumber on the horizontal shredder were air dried in Hodges Laboratory of North Carolina State University. These wood chips were laid out on the floor forming a thin layer for 5 to

7 days. Indoor conditions in Hodges Laboratory were approximately 15°C to 21°C (60°F to 70°F) and 40 to 50 percent relative humidity. Chip moisture content was determined by oven drying using ASTM E871 as a guideline (ASTM International 2006). Chips obtained from size reduction of kiln-dried lumber did not require air drying but equilibrated to the Hodges Laboratory conditions (ovendry moisture content values can be found in Table 1).

Densification

Three factors were evaluated in this part of the experiment: wood species, initial condition of the raw material before primary size reduction, and particle size for densification. The particle size prior to densification was analyzed at two levels: 3 mm (after hammermilling) and 12 to 15 mm (after shredding). Three replicates for each treatment were tested and the average of these replicates was used as a final result. The response parameter evaluated in this part of the experimental design was energy consumption for densification of wood chips.

Wood chips obtained from the shredder and wood particles processed on the hammermill were compacted using a Weima TH514 piston briquetting press. Wood chips and particles were dropped in the hopper of the briquetting press, and an auger then moved the chips into the compacting chamber. Finally, a ram compressed the chips to form the briquettes.

Energy consumption for production of briquettes

In the case of wood size reduction and densification, the electrical energy consumption was calculated from the following mathematical expression:

$$\text{Energy consumption} = \text{power consumption} \times \text{processing period} \qquad (1)$$

In Equation 1, power consumption refers to the rate at which electrical energy is transferred, and processing period is the time that it takes to process completely (comminute or compact) a specific amount of wood by weight (lumber, chips, or particles). Energy consumption, power consumption, and processing period are expressed in joules, watts, and seconds, respectively.

In order to measure the power consumption and processing period of wood size reduction and densification, a data acquisition system was designed. In this data acquisition system, a UPC power cell (Load Controls Inc.) was attached to the electric system of the equipment (shredder, hammermill, or briquetting press) to monitor the load changes (power demand). The power cell then sent a signal with the power demand measurements to a computer. This signal was sent to the computer through a BNC-2110 connector block and a DAQCard-6024E data acquisition card (both from National Instruments). Finally, graphical programming software (LabVIEW, version 8.2, National Instruments) converted, displayed, and recorded the signal sent by the power cell. A DM-100 load meter (Load Controls Inc.) was also connected to the power cell to display real time power consumption.

Table 1.—Thermal energy required for air drying of wood chips.[a]

Wood species	MC (%)		Amount of water evaporated	Energy requirements	
	Initial	Final	(kg H_2O/o.d. kg)	MJ/kg H_2O	MJ/o.d. kg
Eastern white pine	50.9	5.7	0.453	2.96	1.34
Southern yellow pine	27.6	5.9	0.217	2.94	0.64
Yellow poplar	45.9	5.3	0.405	2.98	1.21

[a] MC = ovendry moisture content; o.d. = ovendry.

Energy (heat) required for drying the wood chips and particles was calculated from the flowing expression proposed by Humphrey and Bolton (as cited in Thoemen and Humphrey 2006):

$$H = 2.511 \times 10^{6} - 2.48 \times 10^{3} \cdot T + 1.172 \times 10^{6} \cdot e^{-0.15 \cdot u} \qquad (2)$$

where the thermal energy required to evaporate a unit of bound water, H (J/kg), is expressed as a function of the temperature T (°C) and moisture content u (%).

Calorific values of wood species

The gross and net calorific values of briquettes were determined using a 1341 oxygen bomb calorimeter (Parr Instrument Company) following the procedure provided by the equipment manufacturer (Parr Instrument Company 2008).

Energy balance for production of wood briquettes

The energy requirements for production of wood briquettes (input energy) were associated with the energy required to carry out the basic operations for manufacturing wood briquettes: size reduction, drying, and densification. On the other hand, the energy that could be obtained from combustion of wood briquettes was related to the net calorific value of the raw material (wood species). Mathematically, this can be expressed as follows:

$$E_{\text{shredding}} + E_{\text{hammermilling}} + E_{\text{drying}} + E_{\text{densification}} = E_{\text{briquettes}} \qquad (3)$$

where $E_{\text{shredding}}$ is the energy requirement for shredding of lumber, $E_{\text{hammermilling}}$ is the energy requirement for hammermilling of wood chips, E_{drying} is the energy requirement for drying of wood chips, $E_{\text{densification}}$ is the energy requirement for densification of wood chips and particles, and $E_{\text{briquettes}}$ is the net calorific value of wood.

There were four possible alternatives for densification of woody material:

1. Single size reduction (shredding) of raw material and wood chips densification (12 to 15 mm)
2. Single size reduction (shredding) of the raw material and drying and densification of wood chips (12 to 15 mm)
3. Double size reduction (shredding and hammermilling) of the raw material and densification of wood particles (3 mm)
4. Primary size reduction (shredding) of the raw material, drying of wood chips (12 to 15 mm or 15 to 20 mm), secondary size reduction (hammermilling) of wood chips, and densification of wood particles (3 mm)

Results and Discussion

Size reduction

Shredding.—In the case of wood species, energy consumption for shredding yellow poplar was higher than that for softwoods (Table 2). Higher energy consumption associated with shredding yellow poplar may be attributed to its higher shear strength perpendicular to the grain compared with eastern white pine and southern yellow pine, which suggested that yellow poplar was more difficult to shred than the two softwoods considered in the experimentation (Forest Products Laboratory 1999).

It seemed that energy consumption for size reduction and the final particle size obtained from shredding were inversely proportional (Table 2). Hakkila (1989), Jones (1981), Cadoche and López (1989), and Holtzapple et al. (1989) reported similar conclusions.

With regard to the initial condition of the raw material, shredding dry lumber required more electrical energy than shredding wet lumber except with southern yellow pine, which was the opposite (Table 2). The explanation for these results may lie with the difference in the mechanical properties between dry wood and wet wood. Based on the values of mechanical properties (e.g., modulus of rupture, compression parallel and perpendicular to the grain, and shear parallel and perpendicular to the grain), dry wood (at 12% moisture content) was more difficult to process than wet (green) wood (Forest Products Laboratory 1999).

The highest energy consumption for shredding wood was obtained when dry yellow poplar lumber was processed to obtain 15- to 20-mm chips (0.040 MJ per ovendry [o.d.] kg). In contrast, the lowest energy consumption occurred when wet yellow poplar lumber was shredded to obtain 12- to 15-mm wood chips (0.0212 MJ/o.d. kg).

Hammermilling.—Hammermilling southern yellow pine chips consumed the highest amount of energy among all the species (Table 3), while energy requirements for size reduction of eastern white pine and yellow poplar chips were very similar (Table 3). These results may be explained based on the failure mechanisms undergone by wood chips in the hammermill. Wood chips were exposed to a combination of compression, shear, crushing, and impact forces during hammermilling. Thus, due to the higher compressive strength, shear strength parallel to the grain, impact bending strength, modulus of elasticity and rupture, and hardness of southern yellow pine compared with eastern white pine and yellow poplar (Forest Products Laboratory 1999), energy requirements for hammermilling southern yellow pine were higher than those for hammermilling the other two species.

With regard to chip size, hammermilling 12- to 15-mm wood chips required less energy than hammermilling 15- to 20-mm wood chips (Table 3).

Table 3 shows that processing wood chips that were initially wet required more energy than hammermilling chips obtained from dry lumber. Although it was not studied, it may be possible that the fracture mechanisms of wood during primary size reduction (shredding) might be different depending on the wood species and its initial condition (dry or wet). As a result, properties, shape, and internal structure of chips obtained from dry lumber might be somewhat different than those chips obtained from wet wood.

The highest energy consumption for hammermilling wood chips was attained when 15- to 20-mm wet yellow poplar chips were processed (0.206 MJ/o.d. kg). In contrast, the lowest energy consumption was associated with hammermilling 12- to 15-mm dry yellow poplar chips (0.119 MJ/o.d. kg).

Drying

The thermal energy required to evaporate 1 kg of water was nearly 3 MJ/kg H_2O, regardless of the wood species (Table 1). This value is in accordance with values reported in the literature (Blankenhorn 1980, Wimmerstedt 1999). Moreover, it can be observed that the energy use per unit mass of ovendry material (MJ/o.d. kg) for drying eastern white pine and yellow poplar chips was roughly twice as high as that for southern yellow pine chips. This difference in energy use was attributed to the higher initial moisture content of eastern white pine and yellow poplar compared with southern yellow pine—the more water in wood, the more energy required for drying (moisture content values can be found in Table 1). It is important to note that it was very complicated to determine the exact amount of water in raw material intended for densification because it depended on several parameters such as densification process, equipment, and raw material properties. In the case of

Table 2.—Energy consumption during primary size reduction (shredding).

Factor level combination	Parameters: Wood species	Parameters: Chip size from primary size reduction (mm)	Parameters: Initial condition of raw material	Net energy consumption per unit of ovendry mass (MJ/o.d. kg): No. of observations	Net energy consumption per unit of ovendry mass (MJ/o.d. kg): Mean (SEM)
1	Eastern white pine	12–15	Dry	70	0.0297 (0.0004)
2	Eastern white pine	15–20	Dry	72	0.0293 (0.0004)
3	Eastern white pine	12–15	Wet	111	0.0266 (0.0006)
4	Eastern white pine	15–20	Wet	113	0.0231 (0.0004)
5	Southern yellow pine	12–15	Dry	71	0.0237 (0.0004)
6	Southern yellow pine	15–20	Dry	71	0.0231 (0.0004)
7	Southern yellow pine	12–15	Wet	81	0.0301 (0.0007)
8	Southern yellow pine	15–20	Wet	81	0.0285 (0.0006)
9	Yellow poplar	12–15	Dry	64	0.0401 (0.0007)
10	Yellow poplar	15–20	Dry	72	0.0403 (0.0008)
11	Yellow poplar	12–15	Wet	89	0.0218 (0.0003)
12	Yellow poplar	15–20	Wet	88	0.0231 (0.0003)

Table 3.—Energy consumption during secondary size reduction (hammermilling).

Factor level combination	Parameters: Wood species	Chip size (mm)	Initial condition of raw material	Net energy consumption per unit of ovendry mass (MJ/o.d. kg): No. of observations	Mean (SEM)
1	Eastern white pine	12–15	Dry	9	0.1431 (0.0015)
2	Eastern white pine	15–20	Dry	9	0.1656 (0.0044)
3	Eastern white pine	12–15	Wet	9	0.1747 (0.0066)
4	Eastern white pine	15–20	Wet	9	0.1874 (0.0066)
5	Southern yellow pine	12–15	Dry	8	0.1777 (0.0032)
6	Southern yellow pine	15–20	Dry	9	0.1780 (0.0039)
7	Southern yellow pine	12–15	Wet	9	0.1946 (0.0210)
8	Southern yellow pine	15–20	Wet	7	0.1964 (0.0074)
9	Yellow poplar	12–15	Dry	8	0.1190 (0.0026)
10	Yellow poplar	15–20	Dry	9	0.1523 (0.0021)
11	Yellow poplar	12–15	Wet	8	0.1813 (0.0036)
12	Yellow poplar	15–20	Wet	9	0.2057 (0.0034)

wood, moisture content usually ranges from 8 to 12 percent, which is suitable for wood densification (Karlhager 2008). Thus, a preliminary experiment was carried out to determine the appropriate moisture content for compaction as well as the possibility of compacting wood chips with a moisture content greater than 12 percent. This experiment was performed using green southern yellow pine chips with a moisture content between 15 and 20 percent and chip size of 12 to 15 mm. Particles were compacted using a piston-type briquetting press. Results showed that densification was very poor, to the point that chips did not hold together for long. In fact, briquettes swelled excessively right after coming out of the briquetting press pipeline and eventually disintegrated. These results are in accordance with those of Li and Liu (2000) who reported that, in the case of sawdust, moisture content levels above 13 percent resulted in densified products with low densities that disintegrated easily. Therefore, results obtained in this experiment led to the use of only low moisture content chips (moisture content $\leq$ 12%) in the final experiment. Based on the results from the preliminary research, a low moisture content conditioning room in which the moisture content level was between 5.3 and 5.9 percent was used to air dry the material (Table 1).

Densification

The energy consumption for densification of yellow poplar chips and particles was higher than that for compaction of southern yellow pine chips and particles (Table 4). However, energy requirements for compaction of yellow poplar chips and particles were similar to those of eastern white pine. Interestingly, even though southern yellow pine was more difficult to compress than eastern white pine and yellow poplar based on their mechanical properties, energy consumption for densification of southern yellow pine chips and particles was the lowest among the wood species evaluated.

More energy was also required to compact chips and particles obtained from wet wood (Table 4). As previously mentioned, the condition of the material (wet or dry lumber) when subjected to shredding seemed to affect the properties of the chips obtained after primary size reduction—specifically compressive strength. Once again, it seemed that wood chips and particles obtained from wet lumber were more resistant to compressive stresses than chips and particles obtained from dry wood. Further research is needed to determine the cause of this phenomenon.

Energy requirements for densification of 3-mm wood particles were lower than those associated with 12- to 15-mm wood chips (Table 4). Based on these results, it seemed that less energy was required to compress and compact wood particles (3 mm) than relatively large wood chips (12 to 15 mm). Such results may be mainly ascribed to a couple of factors. First, larger chips were more difficult to convey through the feeding auger than smaller particles, which increased energy requirements for densification of larger particles. Second, it is easier for smaller particles to fill voids within the densified products. Furthermore, Van der Waals forces, which help the densification of the materials, are higher for powdered materials (Cattaneo 2003).

Minimum energy requirements for densification were observed when compacting 3-mm southern yellow pine particles obtained from initially dry lumber (Table 4). Conversely, the maximum energy consumption was generated when compressing 12- to 15-mm wood chips obtained from initially green yellow poplar lumber (Table 4).

Calorific values of wood species

Results from both gross and net calorific values of wood are summarized in Table 5, which shows both values for the softwood species were higher than those for the hardwood species considered in this project. Such values were in accordance with those given in the literature (Harris 1984, White 1987, Bowyer et al. 2007). Higher calorific values associated with softwood species may be attributed to their resin content. In fact, the calorific value of resin in wood is roughly twice as high as that of the wood itself (Bowyer et al. 2007). Therefore, resinous species have higher calorific content than those without resin.

Energy balance for production of wood briquettes

Figure 2 shows the energy requirements for each of the densification alternatives considered in this project:

Alternative 1: Shredding + densification
Alternative 2: Shredding + drying + densification
Alternative 3: Shredding + hammermilling + densification

Table 4.—Energy consumption for densification of wood chips.

	Parameters			Net energy consumption per unit of ovendry mass (MJ/o.d. kg)	
Factor level combination	Wood species	Chip or particle size (mm)	Initial condition of raw material	No. of observations	Mean (SEM)
1	Eastern white pine	12–15	Dry	3	0.1105 (0.0073)
2	Eastern white pine	3	Dry	6	0.0634 (0.0030)
3	Eastern white pine	12–15	Wet	3	0.1134 (0.0036)
4	Eastern white pine	3	Wet	6	0.0774 (0.0024)
5	Southern yellow pine	12–15	Dry	2	0.0896 (0.0005)
6	Southern yellow pine	3	Dry	5	0.0522 (0.0020)
7	Southern yellow pine	12–15	Wet	3	0.1155 (0.0014)
8	Southern yellow pine	3	Wet	6	0.0700 (0.0032)
9	Yellow poplar	12–15	Dry	3	0.1024 (0.0024)
10	Yellow poplar	3	Dry	6	0.1003 (0.0072)
11	Yellow poplar	12–15	Wet	3	0.1184 (0.0027)
12	Yellow poplar	3	Wet	6	0.0683 (0.0012)

Table 5.—Gross and net calorific values of wood species.[a]

Wood species	Gross calorific value (MJ/o.d. kg)	Net calorific value (MJ/kg)
Eastern white pine	21.09 (0.17)	18.78 (0.192)
Southern yellow pine	19.73 (0.05)	17.57 (0.063)
Yellow poplar	18.98 (0.22)	17.04 (0.275)

[a] Values are means (standard deviations). Sample size per species = 6. o.d. = ovendry.

Alternative 4: Shredding + drying + hammermilling + densification

Input energy: The energy required to carry out the basic operations for manufacturing of wood briquettes

Output energy: The energy that can be obtained from combustion of wood briquettes is related to the net calorific value of the raw material (wood species)

As can be observed in Figure 2, the production of briquettes from wood residues is feasible from an energy standpoint because the energy requirements associated with each densification alternative (input energy) did not surpass the amount of energy that can be attained from the combustion of such briquettes (output energy). In fact, the highest energy expenditures were linked to densification of Alternative 4 (1.354 MJ/o.d. kg), which represents less than 8 percent of the energy average of wood considered in this project (18.5 MJ/o.d. kg).

The amount of energy required to produce wood briquettes may depend on the number of manufacturing operations involved in the process. However, as shown in Figure 3, densification in Alternatives 2 and 3 involved the same number of operations, but the energy requirements related to each one were different. Therefore, the amount of energy expenditures for production of wood briquettes is closely related to the type of manufacturing operations in the process. In fact, roughly 80 percent of the energy expenditure associated with densification in Alternative 4 was due to drying of the material (wood chips and particles).

Maximum energy expenditure for production of wood briquettes was associated with the conversion of wet eastern white pine lumber into briquettes through a manufacturing process that included primary size reduction (shredding) of lumber into 15- to 20-mm wood chips, drying of wood chips, secondary size reduction (hammermilling) of the wood chips into 3-mm wood particles, and finally compaction of such wood particles. On the other hand, the minimum energy requirements for production of wood briquettes was attained when dry southern yellow lumber was converted into 12- to 15-mm wood chips through single size reduction (shredding) and subsequently compacted into briquettes.

A statistical analysis was performed to analyze the factors considered in this project and their interactions. This statistical analysis involved an analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$. The model for the ANOVA was built using JMP version 8 from SAS.

Table 6 summarizes the statistical significance of the factors and their interactions. From Table 6, it is clear that all factors experimentally tested in this project were statistically significant, regardless of the response parameter analyzed. Moreover, most of the interactions among the factors studied were also statistically significant (Table 6).

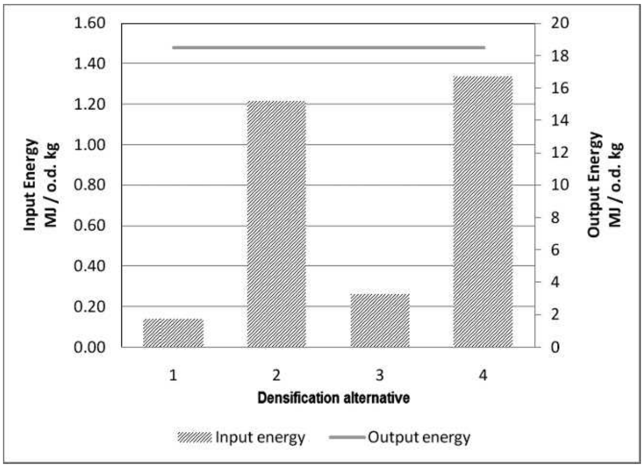

Figure 2.—Energy requirements for each densification alternatives and energy obtained from combustion of wood briquettes. o.d. = ovendry.

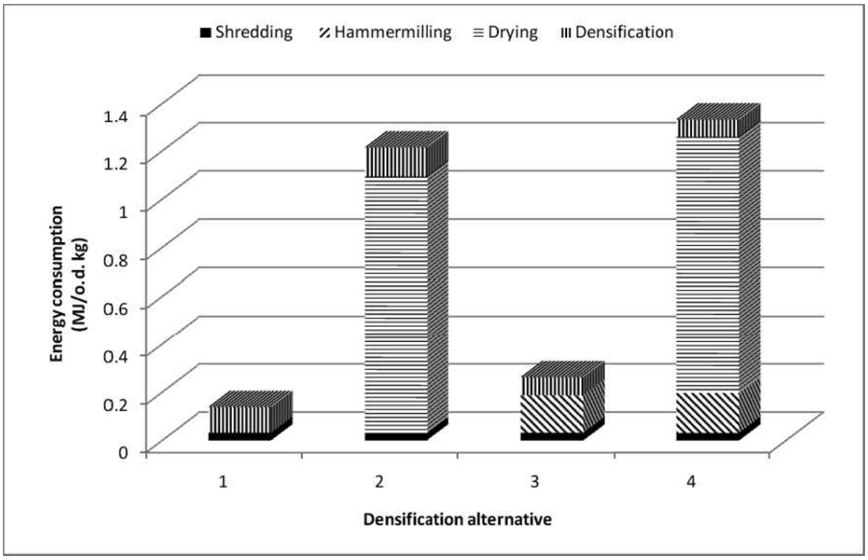

Figure 3.—Energy requirements average per manufacturing operation for each densification alternative. o.d. = ovendry.

Table 6.—Statistical significance (α = 0.05) of factors and interactions with respect to response parameters.

Factors and interactions	Net energy consumption (Pr > *F*)
Shredding	
Wood species	<0.0001
Particle size	0.0136
Initial condition of raw material	<0.0001
Wood species × particle size	0.0016
Wood species × initial condition of raw material	<0.0001
Particle size × initial condition of raw material	0.1074
Wood species × particle size × initial condition of raw material	0.0250
Hammermilling	
Wood species	0.0002
Chip size	0.0006
Initial condition of raw material	<0.0001
Wood species × chip size	0.0449
Wood species × initial condition of raw material	0.0011
Chip size × initial condition of raw material	0.5192
Wood species × chip size × initial condition of raw material	0.8502
Densification	
Wood species	0.0002
Particle size	<0.0001
Initial condition of raw material	0.0081
Wood species × particle size	0.0144
Wood species × initial condition of raw material	0.0001
Particle size × initial condition of raw material	0.0115
Wood species × particle size × initial condition of raw material	<0.0001

Conclusions

This project proved that the production of wood briquettes is feasible from an energy consumption standpoint. Results showed that energy consumption to produce wood briquettes was less than 8 percent of the total amount of energy that can be obtained from their combustion. In addition, the energy expenditures linked to producing wood briquettes were related to the type of manufacturing operations involved in the process. In fact, energy expenditures associated with drying the raw material may account for up to roughly 80 percent of the overall energy requirements for producing wood briquettes. The rest of the energy expenditure for manufacturing wood briquettes was distributed among hammermilling, densification, and shredding, respectively. This study was, however, limited to the production of wood briquettes from mill residues. Additional research is required to determine overall energy expenditures when factoring in the energy needed to obtain and produce mill residues, e.g., harvesting, transport, and milling operations.

Although wood chips obtained from shredding wet lumber were subjected to an air-drying process, hammermilling and densification of such wood chips and particles required more energy than hammermilling and densification of wood chips and particles obtained from kiln-dried lumber. Thus, these results indicate that the initial moisture level of the material prior to primary size reduction (shredding) might affect the properties, shape, and/or internal structure of the chips obtained after shredding as well as on the performance of following manufacturing operations.

The statistical analysis showed that the main effects of all factors considered in this project were significant, regardless of the response parameter analyzed. Furthermore, most of the interactions among such factors were also found to be statistically significant.

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