ABSTRACT

ARRIECHE SUAREZ, RAFAEL EDUARDO. Evaluation of the Energy Balance for the Production of Briquettes from Wood Residues. (Under the direction of Dr. Daniel Saloni and Dr. Richard Lemaster.)

Wood densification consists of processing wood by-products such as sawdust, slabs, chips, etc. into uniform sized particles which are compressed into wood-based fuel products. Pellets and briquettes are some of the most common products obtained through wood densification. The main advantages offered by wood densification are related to handling improvements of residual wood and energy generation opportunities from wood residues. Wood densification can increase the value obtained for wood by-products. However, the process of transforming wood residues into densified products requires large amounts of energy. For this reason, it is necessary to analyze the energy efficiency of converting wood residues into densified products. Therefore, the objective of this study was to evaluate the energy balance for production of briquettes from wood residues.

This research involved the determination of the energy consumption required to carry out the main manufacturing operations for the production of wood briquettes: size reduction, drying, and densification of wood. It was measured the amount of energy that can be obtained from combustion of wood briquettes. In addition, the energy density of wood briquettes was determined. The effects of several factors such as: wood species, material dimensions, moisture content of the raw material on the energy requirements of the operations for manufacture of briquettes and their energy density were studied.

Four different densification strategies were evaluated from an energy consumption standpoint: (1) single size reduction (shredding) of dry lumber and densification of wood chips (12-15 mm in size); (2) single size reduction (shredding) of wet lumber and drying and densification of wood chips (12-15 mm in size); double size reduction (shredding and hammermilling) of dry lumber and densification of wood particles (3 mm in size); (4) primary size reduction (shredding) of wet lumber, drying of wood chips (12-15 mm or 15-12 mm in size), secondary size reduction of wood chips (12-15 mm or 15-12 mm in size), and densification of wood particles (3 mm).

Based on the results of this study, manufacture of briquettes out of wood residues is feasible from an energy consumption perspective. Results showed that when double size reduction, drying, and densification of wood were involved in the production of wood briquettes, the overall energy consumption average represented around seven percent of the overall energy average of wood. Moreover, drying of wood chips and particles may account up to 82 percent of the energy expenditure for the production of wood briquettes.

Evaluation of the Energy Balance for the Production of Briquettes from Wood Residues

by
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DEDICATION

To my parents Rafael e Ydalmy,

my sister Ydaly

and my niece Andrea

BIOGRAPHY

Rafael Eduardo Arrieche Suárez was born in Barquisimeto, Venezuela on July 11th, 1983. He attended to elementary, middle, and high school at “Colegio San Vicente de Paúl” in Barquisimeto, Venezuela. In 2006, he received his bachelor’s degree in Mechanical Engineering at “Universidad Nacional Experimental Politécnica Antonio José de Sucre” (UNEXPO) in Barquisimeto, Venezuela. He graduated with honors after achieving the highest grade point average of his class. In 2008, he began his graduate studies in Wood and Paper Science at North Carolina State University.

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CHAPTER 1

INTRODUCTION

1.1. Background and Problem Statement

Around 1870, wood was the most important fuel source in the United States. As years passed by, the interest in wood as an energy source decreased. Nevertheless, during the 1960's the use of wood as fuel source increased due to the growth of the wood products industry, the increase of the production of wood residues, and environmental legislations that discouraged disposal in landfills as well as open burning of wood wastes. The energy crisis in the 1970's and ensuing oil prices boosted wood energy use and research. In the last decade the economical and environmental concerns have revitalized the interest in wood as an energy source (Hazel & Bardon, 2008). Furthermore, the environmentally friendly nature of wood (low carbon emission from combustion and low metals, sulfur and ash content) has made it a marketable energy source from an environmental perspective.

There are several advantages associated with the use of wood as fuel. For example, wood is a renewable source energy which results in a sustainable supply over the years. Wood is also considered a carbon neutral fuel source (Anglia Biofuels, n.d.). Moreover, wood may be less expensive than many fossil fuels (Anglia Biofuels, n.d.). On the other hand, there are also disadvantages related to the use of wood as an energy source. For instance, the price of wood is particularly variable. In addition, transportation and storage of woody biomass are expensive (Forest Products Laboratory, 2004)

Over the last years, a manufacturing process, called wood densification, has been widely employed to overcome the difficulties faced when wood is used for energy purposes (e.g. handling, storage, and transportation). Wood densification consists of processing wood by-products such as sawdust, slabs, chips, etc. into uniform sized particles which can be compressed into wood-based fuel products (Hassler, Sims, Bean, & Ponzurick, 1990). Most of the advantages offered by wood densification are related to handling improvements of residual wood and energy generation opportunities from wood residues. Moreover, wood densification increases the value of wood by-products such as sawdust, shavings, and chips.

There are several types of densified products. Pellets and briquettes are some of the most common products obtained through wood densification. Both, pellets and briquettes, have similar properties such as bulk and energy density, net calorific value, and moisture and ash content (EUBIA, 2007); (Alakangas, Valtanen, & Levlin, 2006); (Simpkins, 2006). However, pellets are significantly smaller than briquettes. Pellets are cylindrically shaped and smaller (diameter between 6 – 12 mm and length 4 to 5 times the diameter) versus briquettes that are either cylindrically (diameter 25 – 15 mm and length 50 – 400 mm) or parallelepiped shaped and larger (150mm x 70mm x 60mm).

Some studies have been focused on analyzing the energy efficiency of converting wood residues into densified products, especially pellets. For example, Nielsen and Estcourt (2003 as cited by Patzek & Pimentel, 2005) indicates that the inefficient conversion of raw wood into pellets may require up to 80% of the calorific content of oven-dry wood. On the other hand, the energetic effect of burning pellets may be up to 30% less than burning of non-densified wood (Świgoń & Longauer, 2005).

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, especially briquettes. Therefore, a research project intended to study, in detail, the energy consumption along the whole densification process of residual wood for production of briquettes has to be developed. Additionally, this research should analyze the main variables in the production of densified products, especially briquettes.

1.2. Statement of Objective

The objective of this research is to evaluate the energy balance for the production of briquettes from wood residues. Thus, this study is intended to compare the amount of energy required to make briquettes from wood residues – "input energy" – with the amount of energy that these briquettes may provide when they are burned –"output energy".

1.3. Methodology

In order to achieve the research goal, the study is divided into 8 chapters. This structure helps keep a logical flow of the study. A summary of the methodology to be followed in this study is shown below.

<u>Chapter 1: Introduction.</u> This chapter defines the problem to study in this research. The objective and importance of this study are also stated in this chapter. A basic background for this research is covered as well.

Chapter 2: Literature Review. This chapter contains the background needed to carry out this study. This chapter is basically divided into three sections. Each of these sections is focused on the fundamental manufacturing operations that are necessary to convert wood by-products into wood-densified products, that is, size reduction, drying, and densification. The chapter is built based on papers, technical literature, publications linked to the topics just mentioned.

Chapter 3: Experimentation. In this section, the most important variables of this study are identified and defined. This chapter also describes how the variable to be studied are monitored, measured or controlled.

Chapter 4: Results and Analysis. This chapter shows – in the most suitable way – data that is collected from the experiments. In this section, the results obtained from experimentation are discussed. Explanations of these results are also provided based on the background developed in chapter 2.

Chapter 5: Conclusions. Achievements and facts of this research are shown in this chapter. In addition, recommendations and future work are included in this section.

Chapter 6: Recommendations and Future Work. Suggestions regarding the present project and potential research ideas are mentioned in this section.

Chapter 7: References. This chapter refers to the literature cited in this project, such as: books, papers, publications, technical literature, publications, etc.

Chapter 8: Appendices. Supplementary material regarding this project is presented in the appendices.

CHAPTER 2

LITERATURE REVIEW

This chapter is intended to present the necessary background to explain the research. This chapter will be focused on the use of wood as a fuel source. It will also provide an insight into the fundamental concepts of the main manufacturing operations for the production of wood briquettes. Such operations are: size reduction, drying, and densification. Additionally, since the main objective of this project is to evaluate the manufacturing process for production of wood briquettes from an energy perspective, previous work on energy consumption associated with each operation in the production of wood briquettes is also discussed in this chapter.

2.1. Wood as a Fuel Source

Energy from wood biomass can be converted to electricity, heat, or processed fuels (Hewett, 1981). Several technologies are available to make use of wood for energy purposes such as: direct burning, pyrolysis, densification, charcoal and gasification. Nonetheless, direct burning (combustion) is the most effective process to use wood for energy (Zerbe, 2006).

Wood energy consumption reached its highest peak around 1870 and fell gradually to its lowest point in the 1960s (Hewett, 1981). Since then, the use of wood as a source of energy has risen as a result of the rising price of fossil fuels and the growth of the forest products industry (Hewett, 1981). Moreover, environmental legislations that discouraged disposal in landfills as well as open burning of wood wastes has also boosted the use of wood wastes (Tillman, 1978). Over the last decade, growing economic and environmental concerns have also stimulated wood energy use (Hazel & Bardon, 2008).

There are several advantages of using wood as fuel, especially if compared with fossil-based fuels. From an environmental perspective, wood is a renewable source of energy and if replenished is sustainable. Moreover, emissions of carbon dioxide (CO_2) – the most common greenhouse gas – from wood combustion are very low. In addition, low amounts of sulfur contribute to a low probability of acid rain from the combustion of wood. Due to the low ash content in wood, particulate emissions can be controlled by several devices such as cyclone separators, electronic precipitators, and fly-ash injectors (Bergman & Zerbe, 2008).

The major advantage of wood fuels is they are typically less expensive than competing fossil fuels (Bergman & Zerbe, 2008). Although the capital costs associated to wood-burning systems is typically higher than a gas equivalent, a whole life cost analysis shows that biomass tends to end up being less expensive than fossil-based fuels like gas (South Yorkshire Woodfuel, 2009). Even though most wood is manufactured into higher value products, low-value wood and wood residues from manufacturing processes may be suitable for energy applications. In fact, due to the availability of manufacturing residues, using wood as fuel may be less expensive than coal in several applications (Zerbe, 2006). Zerbe (2006) also states that in the case of the United States the use of wood energy is an alternative to reduce the growth of imported fossil fuels.

There are some negatives of using wood as an energy source. The price of wood as a raw material for fuel is extremely variable. Second, the costs associated with transportation of wood from the harvest site to either the wood-processing or wood combustion facility is a fundamental factor to take into consideration when using wood as a fuel (Levan-Green & Livingston, 2001). Wood also requires large space in order to be stored. Thus, along with transportation, storage cost tends to be expensive. In general, fossil fuels tend to be more energy efficient than biomass-based fuels (Hakkila, 1989).

2.2. Wood Densification

Wood densification consists of processing wood by-products such as sawdust, slabs, chips, etc. into uniform sized particles which can be compressed into wood-based fuel products (Hassler et al., 1990).

The main advantage of wood densification is likely its ability to increase the bulk and energy density of non-densified materials such as chips, shavings, sawdust, and so on (European Biomass Industry Association (EUBIA), 2007). For example, density of wood chips is about 200 – 350 kg/m^3 at 30-50% moisture content while bulk density of wood briquettes and pellets – both densified wood products, ranges between 550 and 700 kg/m^3 at 10% moisture content (Karlhager, 2008).

It is important to mention that wood densification is simply a physical transformation that does not change the chemical composition of wood (Tabarés, Ortiz, Granada, & Viar, 2000). Thus, the calorific value of wood is not affected by densification. Nevertheless, since non-densified products exhibit lower bulk density than pellets and briquettes, fluffy materials (e.g. chips, sawdust, etc.) have lower energy density than densified products.

The increase of bulk and energy density obtained through densification is reflected in reduced storage volume, easier handling, lower transportation costs, and more homogeneous composition of densified products (European Biomass Industry Association (EUBIA), 2007). When compared with other fuels, such as oil and coal, the space requirement for forest biomass is considerably large (Figure 2-1). Therefore, it has been suggested to refine biomass into pellets in order to make profitable the transportation of forest fuels over long distances (Hakkila, 2004).

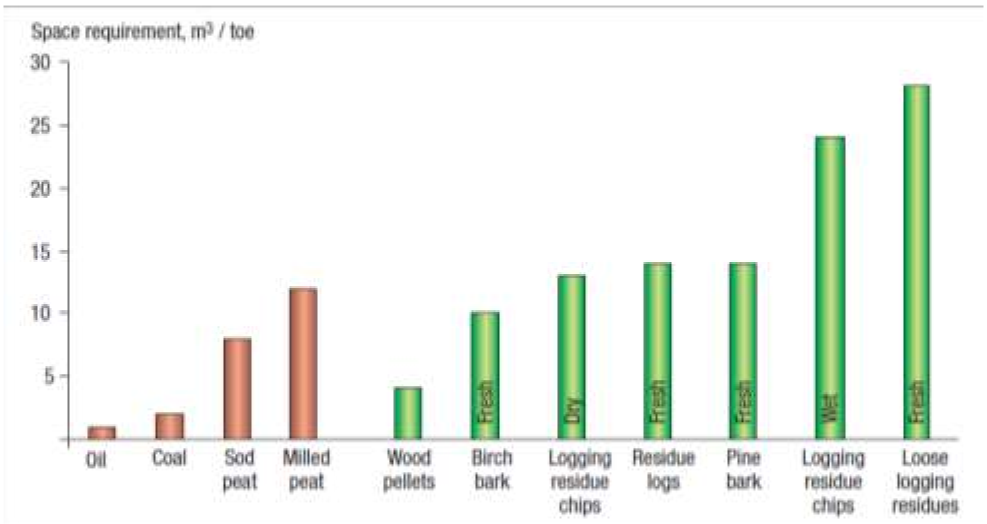

Figure 2-1: Space requirement of several fuels in truck transport (Hakkila, 2004)

In addition to the advantages commented above, wood densification also offers environmental benefits. For example, densified products are very environmental friendly fuels. Life cycle analysis shows that emissions of green house gases from densified products such as briquettes, pellets are only 5-6% of the emission released from an equivalent amount of oil (Raymer 2005 as cited in Karlhager, 2008). It also helps solve the problem of residue disposal (Bhattacharya, 1989).

The process of transforming wood residues into fuel requires large amounts of energy. For example, the conversion of raw wood into pellets may require up to 80% of the calorific content of oven-dry hardwood (Patzek & Pimentel, 2005). Furthermore, heating content value and lifetime of densified wood products is highly affected by its water content (Karlhager, 2008). Figure 2-2 shows how the lower heating value of wood decreases as moisture content in wood increases. Additionally, densified products tend to exhibit negative characteristics during combustion such as: excessive smoke production, poor ignitability, etc. (Bhattacharya, 1989).

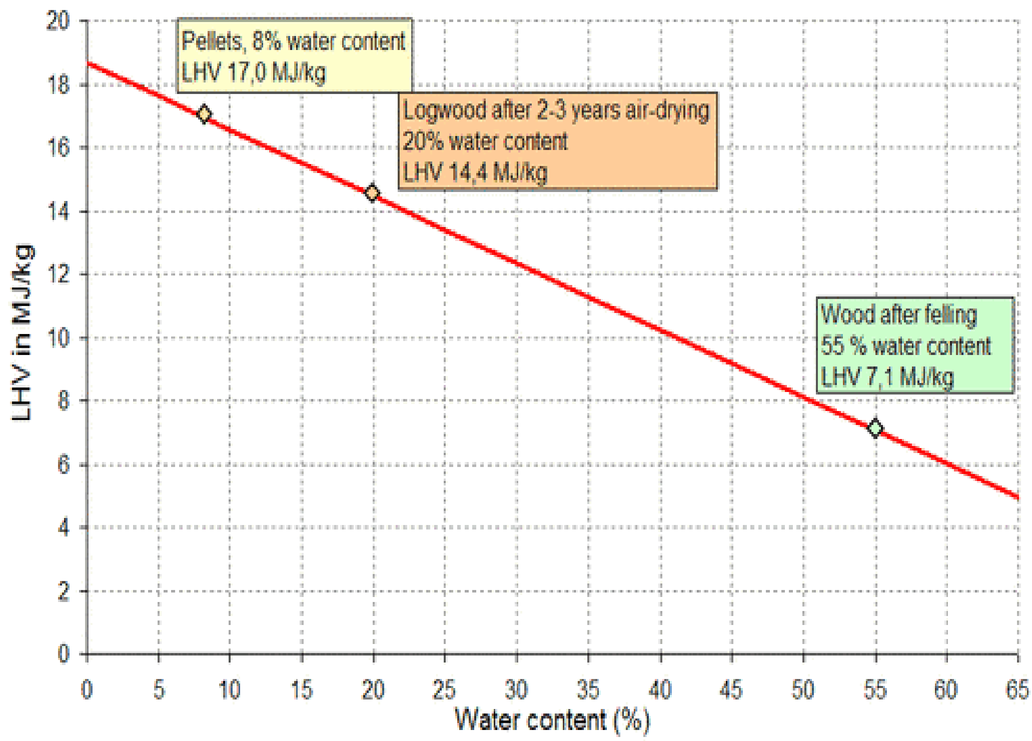

Figure 2-2: Effect of water on lower heating value of wood (European Biomass Industry Association (EUBIA), 2007)

2.2.1. Densified Wood Products

There are several types of densified products. Pellets and briquettes are likely the most common products obtained through wood densification (Figure 2-3). Both products pellets and briquettes share several similarities. For instance, at 10% moisture content, density of wood briquettes is 550 – 650 kg/m^3, compared to pellets at about 600 – 700 kg/m^3 (Karlhager, 2008). Similarly, the energy content of both wooden pellets and briquettes is around 17 MJ/kg (7,265 BTU/lb) at 10% MC wet-basis (Karlhager, 2008).

Figure 2-3: Wood pellets (left) and wood briquettes (right) (European Biomass Industry Association (EUBIA), 2007)

Although both pellets and briquettes have several similarities, there are features than distinguish them from one another. First, both products are different in appearance. Pellets are cylindrical (diameter between 6 – 12 mm and length 4 to 5 times the diameter) while briquettes may be cylindrical (diameter between 25 and 125 mm and length between 50 and 400 mm) or parallelepiped (150mm x 70mm x 60mm). With respect to raw material, pellets and briquettes may be made out of wood and wood residues but in the case of briquettes the raw material tends to be coarser than in pellets (European Biomass Industry Association

(EUBIA), 2007). Thus, briquetting requires less “pre-processing” than pelletizing before the raw material is eventually densified.

Regarding their applications, wood pellets are well suited for using in fully automatic residential and industrial operations, from specialized stoves to large scale combined heat and power plants (European Biomass Industry Association (EUBIA), 2007). On the other hand, briquettes are more suitable for residential applications (Sims, Hassler, & Bean, 1998).

2.3. Wood Densification Process

Figure 2-4 shows the flow diagram of a typical densification process for production of briquettes. As can be seen on Figure 2-4, densification of wood is a multi-operation manufacturing process. In general, the raw material has to fulfill some specific properties such as: size, uniformity, and moisture content before being densified. For this reason, the raw material needs to be “pre-processed” to achieve such conditions. This “pre-processing” 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 itself. As a result, the final products (briquettes or pellets) are obtained.

Figure 2-4: Flow diagram of a densification process for production of briquettes (modified from Hassler et al., 1990)

A study carried out by Reed and Bryant (1978) provides an energy balance for biomass densification. In general, the authors stated that the energy requirements for densification vary between 32 and 80 J/g (44 to 110 BTU/lb) which is about 0.5 – 1% 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 can go up to 5% to 15% of the energy in the raw biomass. In details, if a wood pellet plant is processing 540 tons of wet bark (50% moisture content), the total energy consumption of this process can be broken down as: 814 GJ for drying, 64 GJ for size reduction of bark using 6 hammer mills, and 43 GJ for pelletizing employing 2 pellet mills.

Resch (1982) estimated the energy required to process wood fuels at high moisture content. In this analysis, it is assumed that the initial moisture content of 1 kg of wood fuel is 47% which will be dried up to a moisture content level of 10%. The energy requirements for such drying operation are about 1.64 MJ which may vary depending on the efficiency of the dryers. Once the wood fuel is dried, energy requirements for densification usually range between 0.12 and 0.44 MJ/kg depending on the equipment and wood species (Resch, 1982).

Świgoń and Longauer (2005) stated that drying is the highest energy consumption individual process for production of wood pellets followed by milling and densification. The electrical consumption of milling, drying, and densification is about 144 MJ (40 kWh), 288 MJ (80 kWh), and 72 (20 kWh), respectively (Wach and Kolacz 2003, Pasyniuk 2004 as cited in Świgoń & Longauer, 2005). The authors stated that this operation is a source of unnecessary energy waste because the energetic benefit obtained from drying is lower than the amount of energy invested on such process.

According to Nielsen and Estcourt (2003 as cited in Patzek & Pimentel, 2005), the conversion of wet and fresh stem wood into pellets is the “single biggest energy outlay of an industrial biomass-for energy plantation”. The authors analyzed an example in which a very inefficient plant spent about 16 MJ/kg to transform low quality wood waste into pellets. In other words, the conversion of raw wood into pellets requires roughly 80% of the calorific content of oven-dry hardwood.

Stafford and Livingston (1980) provided power consumption values associated to equipment employed for biomass densification. The authors reported a total of 85 kW (1114 connected horsepower) distributed among production subsystems (dryer system, burner system, hammermill system, pellet mill system, storage transfer, air quality system, and utility systems). It was stated in this study that the electrical energy demand accounts for 2,640 MJ per hour (2.5 million BTU per hour). The authors also suggested that hammermill horsepower may be reduced by using larger hammermill screen opening and drying the material to a lower moisture content level. Similarly, Miles (1980) stated that power requirements for the densification alone are about two to three times lower than that of the entire production systems. It was reported that while power demand range between 0.13 and 0.36 MJ/kg (37 and 100 KW/ton) for densifiers, power demand is about 55- 240 kW/ton for a densified product.

The European Biomass Industry Association (2007) reports 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 for wood pelletizing is about 4.1 MJ/kg (1,140 kWh per ton) of pellets which can be mainly broken down into 0.29 – 0.54 MJ/kg (80 – 150 kWh/ton) for electricity and about 3.42 MJ of heat per kg (950 kWh of heat per ton) of water to be vaporized. Such numbers are summarized on Figure 2-5

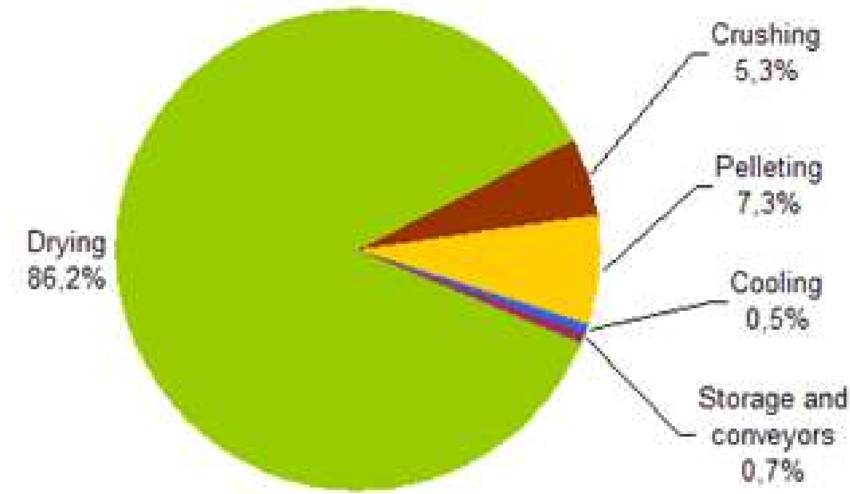

Figure 2-5: Energy consumption distribution for production of wood pellets (European Biomass Industry Association (EUBIA), 2007)

Thek and Obernberger (Thek, 2004) analyzed several case scenarios for the production of wood pellets. Case scenarios studied by Thek and Obernberger were divided based on the operational processes required for pelletizing. For example, in the case in which wet raw material was used, drying was necessary. Under these conditions, specific electricity consumption roughly varied between 0.46 and 0.58 MJ/kg (128 and 160 kWh per ton) of pellets depending on the scenario being analyzed. On the other hand, when dry raw material was employed – no drying included in the production line – the specific electricity consumption ranged from about 0.27 to 0.47 MJ.kg (75 to 130 kWh per ton) of pellets.

Since size reduction, drying, and densification of the raw material consume most of the energy employed for the production of wood densified products (Świgoń & Longauer, 2005), these manufacturing operations will be discussed in detail from an energy standpoint in the following paragraphs.

2.3.1. Size Reduction

Size reduction refers to the reduction of forest biomass by mechanical means into higher valued and relatively uniform bulk material to be used for industrial processing, fuel, or fodder (Hakkila, 1989). Size reduction of wood may also be referred to as comminution of wood.

2.3.1.1. Factors affecting the energy consumption for size reduction operations

Regardless of the wood size reduction technique used to generate particles, the amount of energy required to separate chips from the substrate is an important variable to take into consideration. The energy consumption in size reduction of wood is also referred as specific comminution energy which is the amount of energy required to comminute a standard mass of volume of wood and bark (Forest Products Research Society, 1985).

The energy requirements to perform wood size reduction operations are affected by several factors. Among these factors, particle size, specific gravity (density), cutting speed and direction, knife configuration, wood temperature, and moisture content may be mentioned (Forest Products Research Society, 1985).

2.3.1.1.1. Final particle size

Final particle size is one of the most important factors affecting the energy requirements for size reduction operations of wood. The relationship between particle size and energy is that the smaller the final particles, the higher the energy consumption (Hakkila, 1989). This fact can be observed on Figure 2-6 in which energy requirements of a disk chipper are shown.

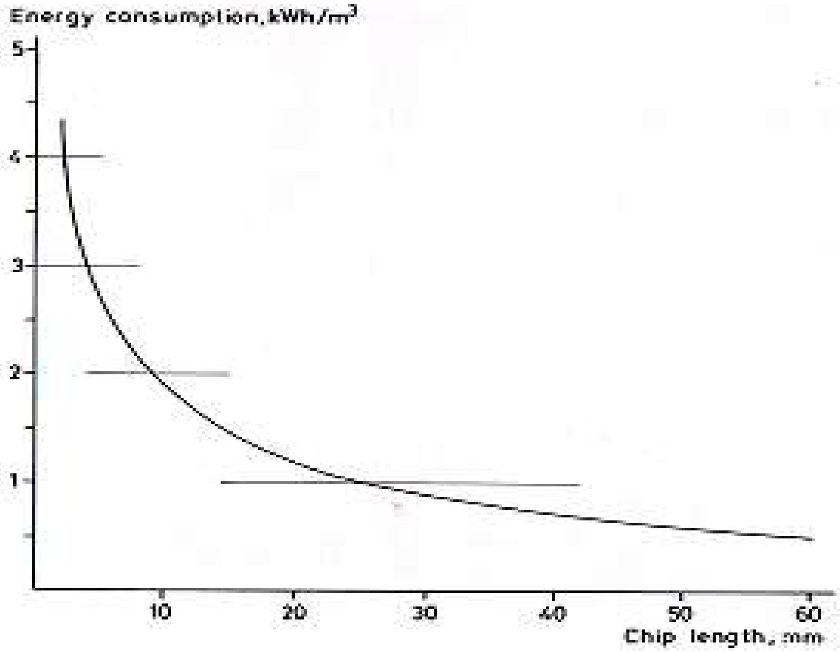

Figure 2-6: Effect of particle length on energy consumption (Hakkila, 1989)

Jones (1981) compared energy requirements of several size reduction equipment based on the nominal size of particles generated by each. As can be seen on Figure 2-7, results obtained by Jones (1981) showed that energy requirements increased as the final particle size decreased.

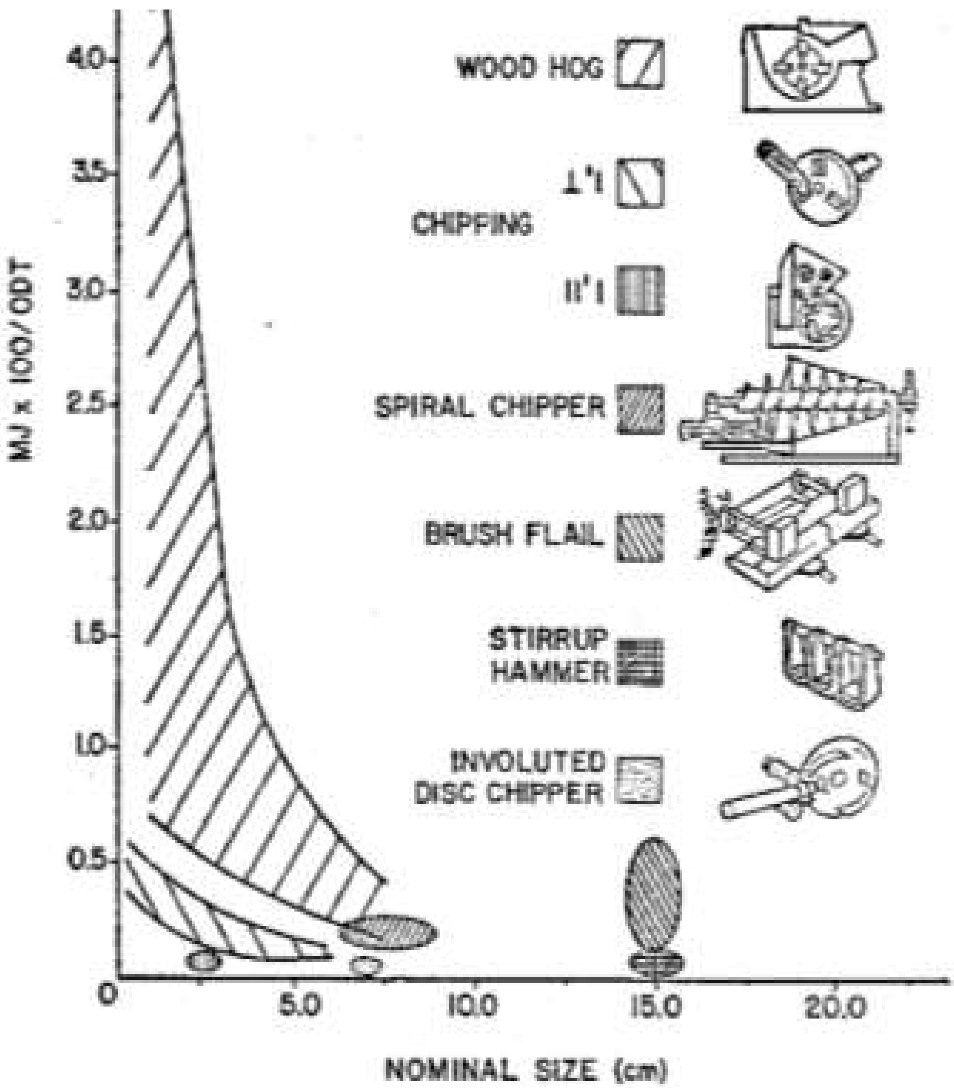

Figure 2-7: Comparison of machine energy requirements for wood size reduction (Jones, 1981)

In another study, Cadoche and López (1989) quantified the energy consumption for size reduction of hardwoods and agricultural wastes as a function of final particle size and ratio of comminution. Experiments were carried out using a hammer mill and a knife mill. Data obtained in this study related to hardwood size reduction is summarized in Table 2-1

Table 2-1: Energy requirements for size reduction of hardwoods (Cadoche & López, 1989)

Material	Equipment	Ratio of comminution	Final size (mm)	Energy consumption (MJ/kg)	Energy consumption (KWh/ton)
Harwood	Knife Mill	14 · 0	1.6	0.468	130
		9 · 0	2.54	0.288	80
		7 · 0	3.2	0.180	50
		3 · 5	6.35	0.90	25
		2 · 5	9.5	0.54	15
		9 · 0	12.7	0.288	8
	Hammer mill	14 · 0	1.6	0.468	130
		9 · 0	2.54	0.432	120
		7 · 0	3.2	0.414	115
		3 · 5	6.35	0.342	95

Cadoche and López (1989) pointed to two facts from their study. First, the authors concluded that correlation between energy consumption and degree of size reduction is not always linear (Figure 2-8). Moreover, the authors stated that this relationship depends on the types of raw material and size reduction equipment used.

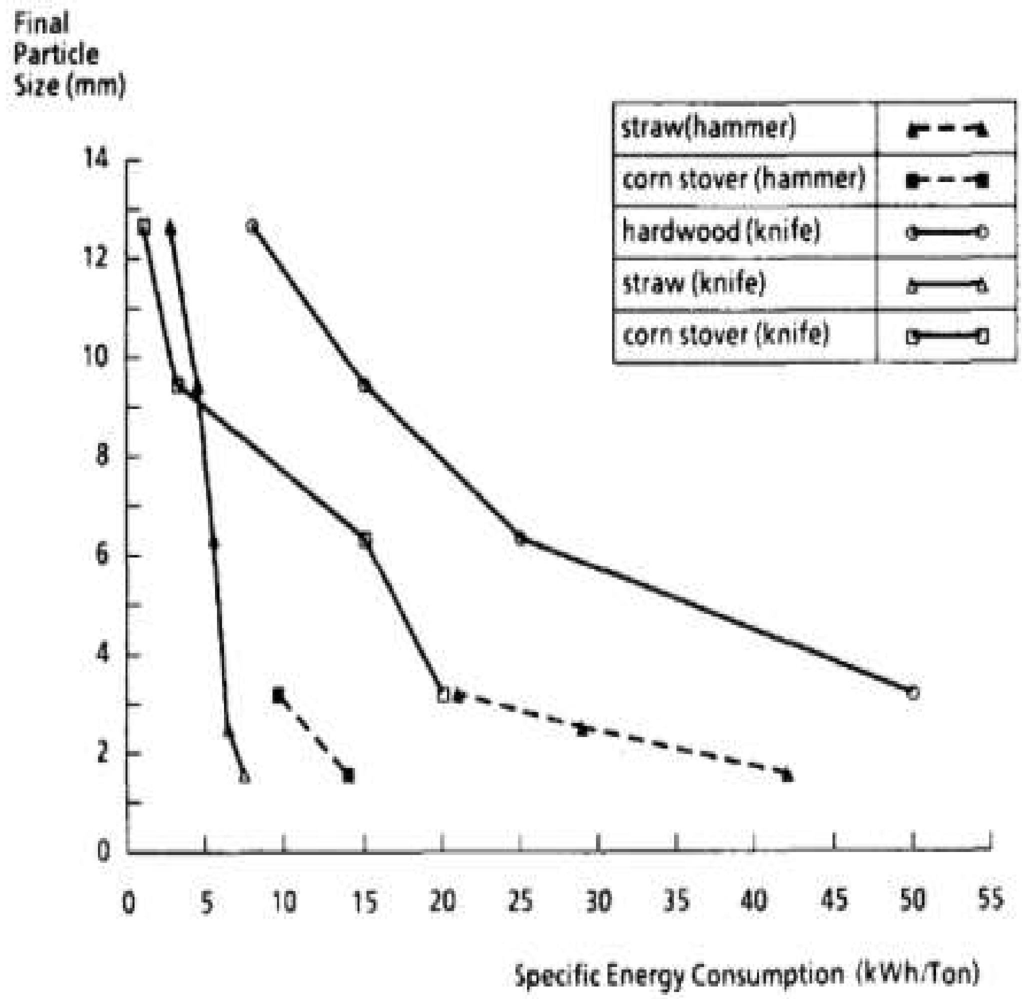

Figure 2-8: Size reduction of lignocellulosic materials with hammer and knife mills (Cadoche & López, 1989)

Holtzapple at el. (1989) also analyzed the energy requirements for size reduction of woody biomass. This studied compared the energy requirements for conventional methods of mechanical size reduction (attrition mill and hammer mill) with those energy requirements associated to a wood planer. Additionally, energy requirements for a non-mechanical size reduction method (explosive depressurization) were studied.

In the case of conventional methods of mechanical size reduction, estimates of the energy requirements were obtained from equipment manufacturers. Such estimates are based on the following equation which relates energy required for grinding to particle size:

$$E = -0.731 \ln L + 0.742 \qquad \text{(Eq. 2.1)}$$

where E is the grinding energy (MJ/kg dry wood) and L is the length (mm) of a wood cube that would just fit through the sieve opening. Equipments manufacturer's estimates are summarized on Table 2-2.

Table 2-2: Conventional energy requirements for size reduction (Holtzapple et al., 1989)

Method	Product particle size	Length (mm)	Electrical energy requirement (MJ/kg)	Equivalent heat requirement (MJ/kg)
Two-stage double disk attrition mill	140	0.106	2.6	7.08
Attrition mill	20	0.85	0.94	2.82
Two-stage hammer mill	10	2	0.18	0.54

On the other hand, electric power measurements of the wood planer were taken at three different depths of cut: 0.76, 1.5, and 2.3 mm. Samples were made out of air-dried poplar with diameters of 10 cm. Data obtained from this experiment is shown in Table 2-3. It is important to point out that these power measurements were subtracted from the non-load power requirement of 500 W.

Table 2-3: Planer power requirement and production rates (Holtzapple et al., 1989)

Depth of cut (mm)	Production rate (g/s)	Power requirement (W)	Net power requirement (W)	Electrical energy requirement (MJ/kg)	Equivalent heat requirement (MJ/kg)
0.76	6.4	840	340	0.053	0.159
1.5	12.7	1400	900	0.071	0.213
2.3	18.7	1680	1180	0.063	0.189

In order to compare the performances of both methods of mechanical size reduction, it was necessary to establish a common basis (unit). Thus, the increase in the specific surface area from the starting material to the final product was used as common basis. Figure 2-9 shows the comparison of the energy requirements for the conventional mechanical size reduction techniques, the wood planner, and the explosive depressurization method. It was concluded in this report that the wood planer seems to reduce the size of wood with lower energy requirements than conventional mechanical methods. Nonetheless, the wood planner is not capable to produce particles as fine as attrition mills.

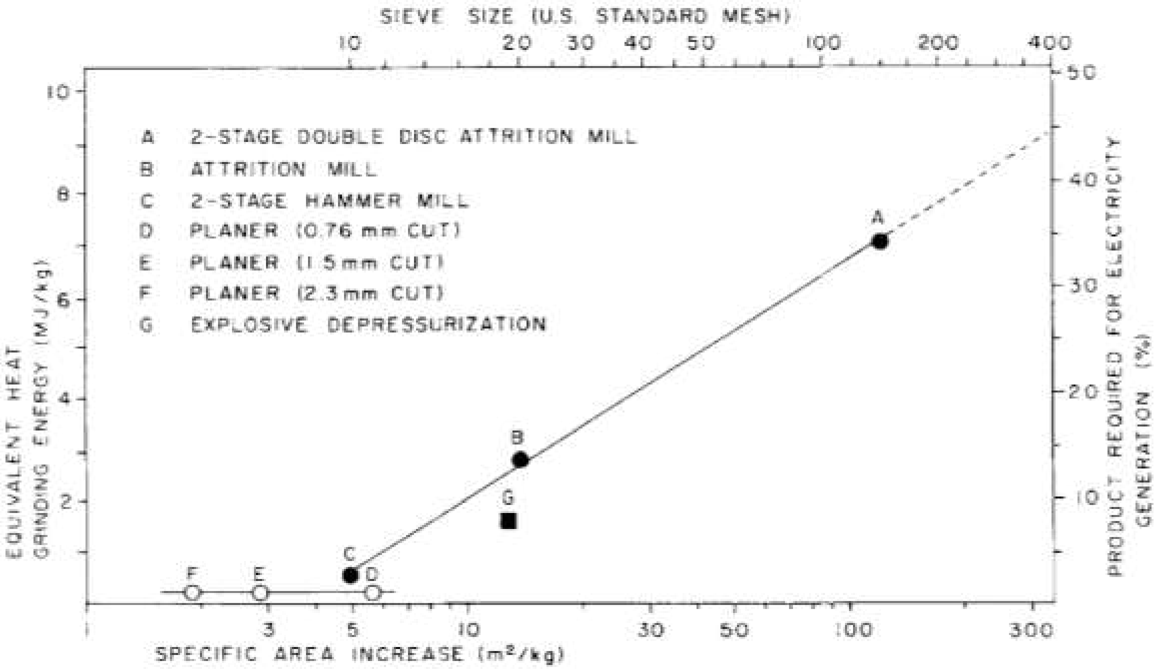

Figure 2-9: Comparison of size reduction energy requirements on basis of specific area increase (Holtzapple et al., 1989)

2.3.1.1.2. Wood species

Other important parameters to consider for size reduction of wood are wood species and physical properties of wood, specifically density. With regard to wood species, fuel consumption and power requirements are higher for hardwoods than for softwoods (Rodgers 1948 as cited in Hakkila, 1989). Cadoche and López (1989) analyzed the energy consumption for size reduction of hardwoods and agricultural wastes out using a hammer mill and a knife mill. The authors stated that regardless of the final particle size and the equipment employed, size reduction of hardwoods requires considerably higher energy than for agricultural wastes such as straw and corn stover.

In a study carried out by Esteban and Carrasco (2006), energy requirements of comminuting forest biomass into fine products suitable to feed pulverized fuels burners were analyzed. Four different types of circuit processes were defined in this study in order to determine the most efficient way to reduce raw material into the desired dimensions. Equipment employed in this study consisted of two hammer mills, one screener, and one dynamic air separator. Poplar chips, pine chips, and pine bark were the three types of forest biomass analyzed in this investigation. Energy requirements of the machines employed in this study were defined as the work realized by each piece of equipment expressed in terms of the specific active electric energy used by the motor per unit of mass of the oven-dry biomass. Mathematically, the definition may be expressed as:

$$E = \frac{1.372 \cdot VI \cdot \cos\,\varphi T}{1000 \cdot M} \qquad \text{(Eq. 2.2)}$$

where E is the specific energy in kWh o.d. t^{-1}, V is the voltage (volts), I is the current (amperes), cos φ is the power factor, T is the duration of the experiment (hours), and M is the oven-dry mass of the material being processed (metric tons).

Average values of energy requirements to process each type of biomass were reported as follows: 0.31 MJ/o.d. kg (85.4 kW h o.d. t^{-1}) for poplar chips, 0.43 MJ/o.d. kg (118.5 kWh o.d. t^{-1}) for pine chips, and 0.07 MJ/o.d. kg (19.7 kW h o.d. t^{-1}) for pine bark. The authors attributed the difference in the energy required to process each type of biomass to its physical and mechanical properties. For example, even though pines chips and polar chips exhibit similar behavior, higher energy requirements associated with pine chips were attributed to the difference in bulk density, moisture content, and higher mean particle size if compared to poplar chips. In the case of pine barks, lower energy requirements were obtained due to its brittle nature.

In general, Trass (1984) stated that breakage of wood is considerably different from the breakage of bark when he used a planetary ring-roller mill for grinding of bark to fine powders.

On the other hand, the correlation between density of wood and specific energy of size reduction operations has been reported to be proportional and linear (Figure 2-10).

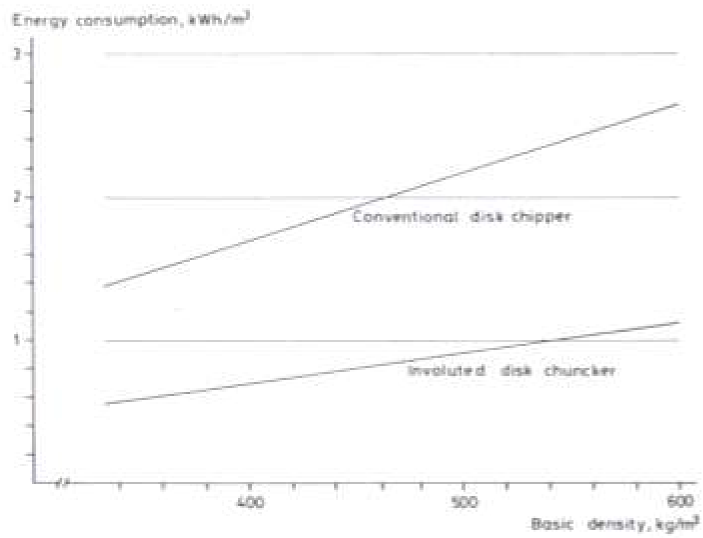

Figure 2-10: Effect of density of wood on energy consumption (Hakkila, 1989)

2.3.1.1.3. Temperature

It is well known that temperature affects the mechanical properties of wood in such a way that wood strength reduces as temperature increases. This aspect of wood behavior is very important in developing energy-efficient techniques for size reduction of wood such as defibration of wood subjected to high temperature (Forest Products Research Society, 1985).

It has been reported that size reduction of frozen wood requires more energy than size reduction of not frozen wood (Hakkila, 1989)

2.3.1.1.4. Cutting direction

Relative motion and orientation of the cutting tool with respect to the wood piece may also affect the energy requirements during size reduction operations (Forest Products Research Society, 1985). For example, energy requirements are lower when the cutting edge is parallel oriented to the grain and travels perpendicularly to it (cutting mode 0-90) than when the cutting edge is oriented and moved perpendicular to the grain (cutting mode 90-90) (Forest Products Research Society, 1985) . Energy requirements for a cutting tool with its edge perpendicular oriented to the grain and moving parallel to the grain (cutting mode 90-0) will be between the previously mentioned cutting modes (Forest Products Research Society, 1985).

Relative motion and orientation of the cutting tool is extremely related to the mode of size reduction. Thus, it is not surprising that the mode of size reduction has an important bearing in the energy requirements for size reduction of wood – as it was mentioned above, In fact, Jones (1981) analyzed the energy requirements of baling assuming bales are formed by shearing. Based on these studies, Jones reported that the shearing energy required to form pine slash bales is about 1.4 MJ per oven dry ton. Experimental data obtained using a specialized crusher (TVA Fiberizer) to crush 1.7 m long round bolts, 9-18 cm in diameter, into slivers about 3 cm in cross section shows that the energy required to perform such operation range between 40 and 70 MJ/ton (ovendry). After some modifications carried out on the previously mentioned equipment in order to concentrate more of the energy required on splitting rather than on crushing, energy requirements were reduced to values of 23-32 MJ/ton (ovendry).

2.3.1.1.5. Knife configuration

The effect of knife configuration on the energy requirements to comminute wood is observed on the rake and clearance angles of the knives. For instance, energy is minimized when large rake angles are used while dull knives tend to increase it. Ideally, clearance angles should be not less than 6 degrees if the objective is to reduce the energy requirements for wood size reduction (Forest Products Research Society, 1985).

2.3.1.1.6. Cutting speed

The effect of cutting speed on energy requirements is not very well defined. It has been reported that high cutting speed 5 – 45.7 m/sec (1,000 – 9,000 ft/min) has little effect on cutting forces while low cutting speed 0.035 – 5 m/sec (7 – 1,000 ft/min) may increase up to 2.5 times cutting forces (Forest Products Research Society, 1985). Nevertheless, other sources state an increase of energy consumption with increasing cutting speed of a drum chipper (Hakkila, 1989). The latter information can be observed on Figure 2-11.

Trass (1984) reported that in the case of bark, specific energy could be lowered through lower rotational speed (rpm) and high feed rates. In his studies, Trass used a planetary ring-roller mill for grinding of bark to fine powders.

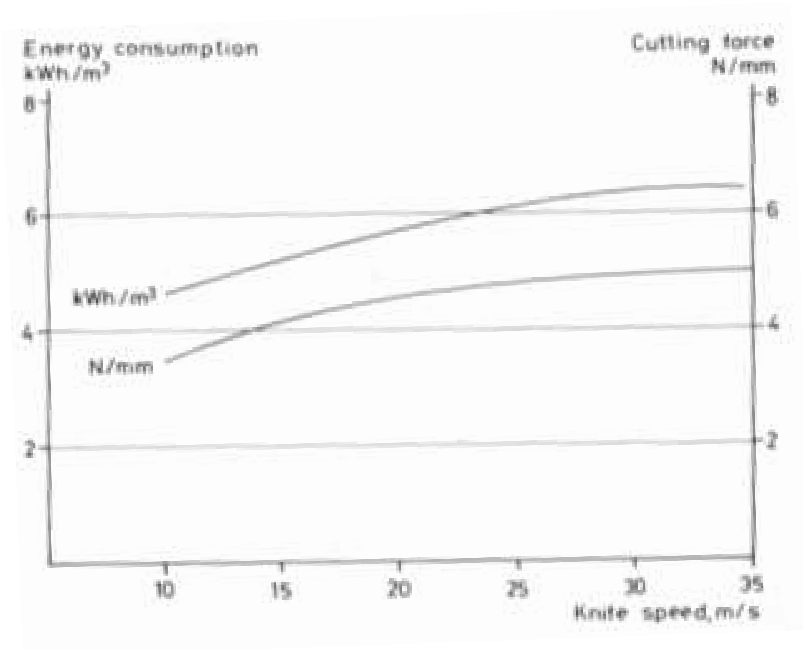

Figure 2-11: Effect of knife speed on cutting forces (Hakkila, 1989)

2.3.1.1.7. Moisture content

Similar to the case of cutting speed, the effect of moisture content of wood on energy requirements is not well established. Koch (1985) stated that even though mechanical properties of wood are inversely proportion to moisture content and that dry lumber is stiffer and stronger than freshly cut green lumber, size reduction of wood is not simply related to moisture content. He mentioned that dry wood residues require less energy to be ground to fine mesh size than green wood residues.

Similarly, Trass (1984) observed there was an increase in power consumption when moisture content was greater than 35%. Trass analyzed the specific energy consumption for grinding of wood chips and bark to fine powders using a planetary ring-roller mill. The author explained that wet materials tend to stick on the grinding surface which increases friction and reduces the efficiency of the operation. Trass suggested that the specific energy consumption may be reduced by decreasing non-load energy consumption.

In contrast, Hakkila (1989) states that reduction of moisture content of wood to levels below fiber saturation point raises specific energy of a disk chipper (Figure 2-12)

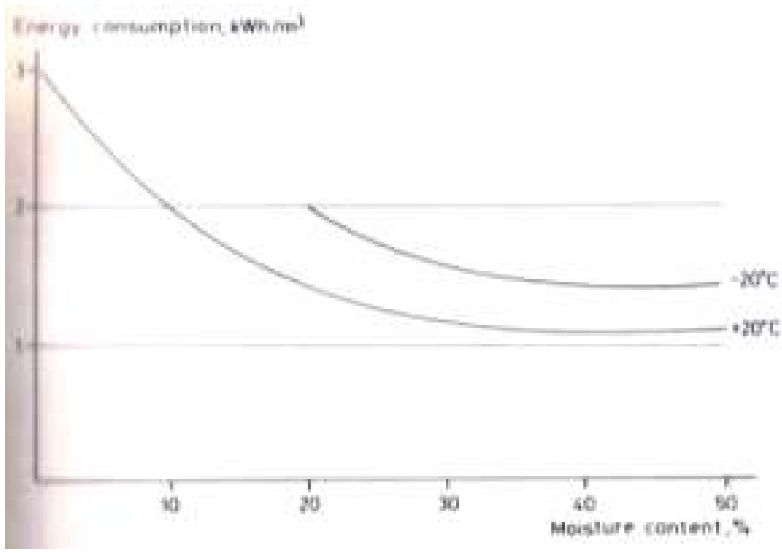

Figure 2-12: Effect of moisture content of wood on energy consumption (Hakkila, 1989)

In addition, the interaction between wood species and moisture content seems to have an important bearing on the power consumption of machining operations. For instance, it has been reported that saturated Douglas fir and sugar samples require larger cutting forces during machining – which means higher power demand – compared to dry samples of the same species. Conversely, saturated yellow birch and white ash samples require smaller cutting forces than dry samples under the same machining conditions (Koch, 1964). Koch (1964) explained that increased moisture content causes Douglas fir and sugar pine to have larger friction coefficients compared to dry values while the reverse may be true for the case of birch and white ash

2.3.2. Drying

Drying refers to the reduction of the amount of moist of water in wood. The main objective is to achieve uniform moisture content in the material at the end of the drying process. Drying is necessary in the production of briquettes due to technological reasons linked to the manufacturing process as well as storing and transportation reasons (Wimmerstedt, 2007). Additionally, reduction in the moisture content will make the biofuel less susceptible to mould and insect attacks during storage (Stahl, Granström, Berghel, & Renström, 2004).

In contrast to lumber drying where drying takes several days, drying of wood particles takes place in minutes, even seconds. While special attention is paid to wet-bulb and dry-bulb temperatures (Maloney, 1993) in the drying of lumber, drying of wood particles is monitored by controlling: drying medium temperature and humidity, exposure time of products, and physical properties and characteristics of product (Corder, 1958). The principle of drying of wood particles is to rapidly move them through a high temperature drying medium. Consequently, drying of wood particles takes short periods of time since a maximum surface area exposure of the material is attained by this drying principle. It is important to mention that most of drying equipment available today – almost without exception – applies the just-mentioned drying principle (Maloney, 1993).

Drying equipment used for biofuels can be classified based on the medium used in the drying process (Stahl et al., 2004). Such classification divides drying equipment into flue gas dryers and steam dryers. Rotary dryers (Figure 2-13), which belong to the category of flue gas type dryers, dominate the market of drying equipment (Wimmerstedt, 1999). Besides rotary dryers, cascade dryers and flash dryers are also flue gas type dryers.

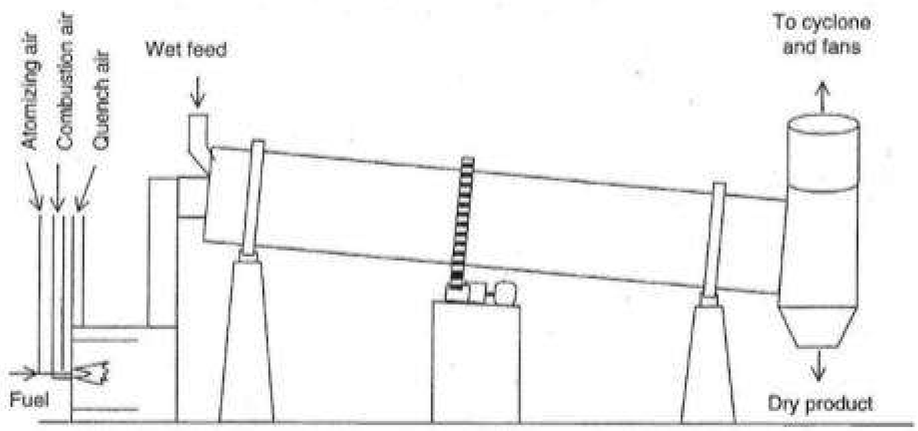

Figure 2-13: Simplified diagram of direct-heat rotary dryer (Krokida, Marinos-Kouris, & Mujumdar, 2007)

2.3.2.1. <u>Factors to consider for drying of woody biomass</u>

As in any other process, many variables influence drying of wood particles. Initial moisture content of the material, particle geometry, variable ambient conditions, and feeding system are some operational factors that affect drying of wood particles. Such factors are discussed in detail in the following paragraphs. On the other hand, economics of drying depends on different factors such as: fuel cost, equipment cost, labor requirements, inlet temperature, initial and final moisture content, size and shape of the particles, efficiency of the drying equipment, and personnel abilities. As it can be seen, some variables affect not only drying operation itself but also its economics.

2.3.1.2.1. Initial moisture content

Several parameters have to be taken into consideration when evaluating the initial moisture content of the material. First, moisture content of the raw material depends considerably on the source of the raw material. For example, raw material obtained from green wood is expected to have higher moisture content than wood by-products from previously dried materials such as: planer shavings, sawdust, sander dust, etc.

Similarly, wood species has a significant effect on the green moisture content of the material (Maloney, 1993). For instance, green moisture content of pines ranges between 80 and 200% (oven-dried basis) while green moisture content of Douglas fir is about 40% (Maloney, 1993). Among hardwood species, green moisture content variation is not as great as in softwoods (Maloney, 1993). Furthermore, there is a major difference in green moisture content between sapwood and heartwood for a particular species (Maloney, 1993).

In addition, the average initial moisture content is very important, especially from an economic perspective. If the average initial moisture is higher than the outlet moisture content, larger drying equipment will be required to produce a given quantity of dry material.

Variation in the initial moisture content of the material is a very important factor as well. Let us assume that there is a large variation in the initial moisture content of the material. If the proportion of wet material is higher than the proportional of “dry” material for a given amount of particles to dry, there will be a tendency to over-dry the material. On the other hand, if the proportion of wet material is lower than the proportional of "dry" material, there will be a tendency to discharge the material at a higher than desired moisture content level. Therefore, having a relatively uniform moisture content of the raw material entering the dryer is critical in order to dry wood particles to a uniform moisture content level.

2.3.1.2.2. Particle geometry

The size and shape of the particles to be dried are also important factors that affect drying processes. Since the main objective of any drying operation is to reduce the moisture content of the material being dried, increasing the size of the particles of a given shape will tend to increase the cost of drying (Maloney, 1993). The explanation for this tendency is that larger particles require more heat to remove a given percentage of moisture due to less surface area exposure per unit of volume and time. Moreover, if the proportion of large particles is higher than the proportion of small particles, there will be a tendency to over-dry small size particles. Unfortunately, it is very difficult to achieve uniformity in particle configuration regardless of the raw material processing operation. It has been reported that the time required to heat a spherical particle varies as the square of its diameter (Parry et al. (1950) as cited in Corder, 1958). For instance, a sawdust particle of 1.3 mm (1/20 inch) in diameter will be heated in about 1 second while particles of 3.175 mm (1/8 inch) and 25.4 mm (1 inch) in diameter will require about 5 seconds and 6 minutes, respectively (Parry et al. (1950) as cited in Corder, 1958). Moreover, when drying of wood particles less than 6.35 mm (¼ inch) thick, drying rates are governed by heat transfer rather than diffusion (Fleischer

(1953) as cited in Corder, 1958). Therefore, inattention to these factors (size and shape) may end up being very troublesome in both operational and economic perspectives.

2.3.1.2.3. Feeding system

The method of feeding the raw material into the dryer may also have some effects on the uniformity in the moisture content of the dried particles. Nearly all feeding systems use a volumetric rather than a weight based approach to introduce the material into the dryer (Maloney, 1993). However, the major concern with this volumetric principle is the influence of bulk density on the raw material and short-term volume changes. For example, an increase in the bulk density of the material will result in a higher evaporable load on the dryer.

2.3.1.2.4. Ambient conditions

Last but not least is the effect of ambient conditions of the drying process. Changes in the ambient temperature and humidity conditions will require adjustments in the dryer inlet temperature in order to maintain the constant final moisture content. This fact is very important to consider in area such as the southern United States where is common to have frequently fluctuations in the relative humidity (Maloney, 1993).

2.3.2.2. <u>Energy consumption for drying of wood</u>

In general, drying of material is energy intensive – especially when dealing with wood – because a large amount of energy is required to evaporate water (Simpson & Forest Products Laboratory, 1991). The amount of energy used in drying operations depends on several factors such as amount of water to be evaporated, dryer design, drying procedure, maintenance of drying equipment, etc. All these factors have a significant bearing on the drying of wood particles, but the amount of water to be evaporated is by far the most important factor (Comstock, 1975).

Basic energy requirements for wood and water heating may be divided into several areas. In general, energy use in drying consist of: latent heat of evaporation, differential heat of sorption, sensible heat, heat lost by exhausting of air, heat lost by convection and radiation from the dryer's walls, and other heat losses such as: leaks, steam spray, etc (Comstock, 1975). At this point, it is important to remark that energy requirements during drying operations are usually expressed as energy required per unit of mass of water evaporated.

2.3.1.3.1. Latent heat of evaporation and differential heat of sorption

The heat required to vaporize the water refers to the energy used to convert the water in wood from liquid or bound water phase to a vapor phase (Comstock, 1975). When moisture content of wood is above the fiber saturation point, heat required to vaporize water is purely the latent heat of evaporation. For drying, the latent heat of evaporation of water is roughly 2.3 MJ per kilogram of evaporated water (1000 BTU per pound of water evaporated). This value – at low temperatures – decreases as a function of temperature, that is, the latent heat of evaporation will be lower at higher temperature (Simpson & Forest Products Laboratory, 1991). On the other hand, when the moisture content of wood is below the fiber saturation point, the differential heat of sorption – or simply heat of sorption – must be added to the latent heat of evaporation (Comstock, 1975). The differential heat of sorption is also called heat of wetting. The magnitude of the differential heat of sorption tends to decrease as temperature increases at moisture contents above 5 % (Stamm and

Loughborough, 1935 as cited in Skaar, 1988). Briefly, the heat required to vaporize water in wood can be divided into latent heat of evaporation and differential heat of sorption. The latent heat of evaporation is associated with the evaporation of the free water in wood while the differential heat of sorption is linked to the removal of bound water in wood. Figure 2-14 shows the energy required to evaporate water from wood as a function of moisture content. For most drying, the differential heat of sorption is ignored (Comstock, 1975).

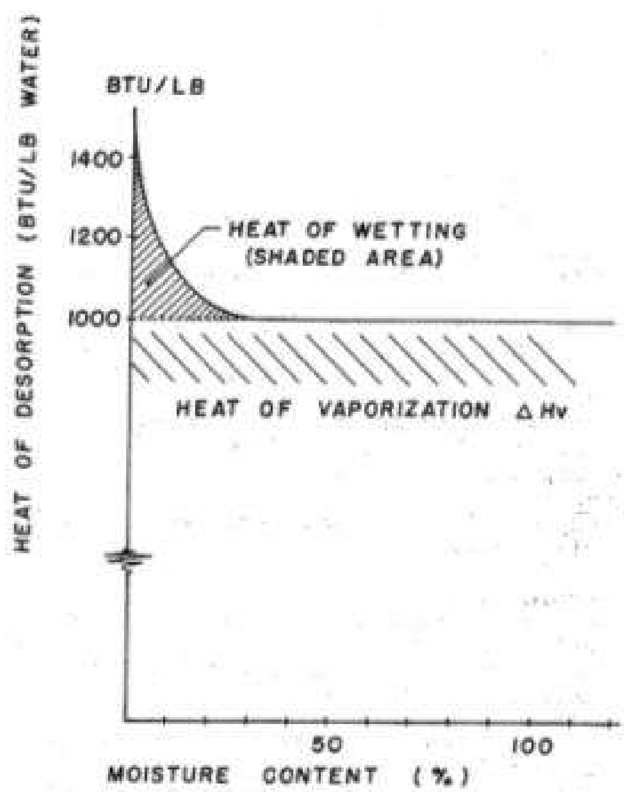

Figure 2-14: Energy required to evaporate water from wood as a function of moisture content (Comstock, 1975)

Several equations and models have been reported to estimate values for both latent heat of evaporation and differential heat of sorption. For instance, Keenan et al. (1969 as cited in Simpson & Forest Products Laboratory, 1991) proposed the following equation to determine the latent heat of vaporization as a function of temperature:

$$\lambda = 1{,}075.4 - 0.58 \cdot (t - 32) \qquad \text{(Eq. 2.3)}$$

where:

- ✓ λ = latent heat of vaporization (BTU/lb H_2O)
- ✓ t = temperature (°F)

In the same way, (Brown, Panshin, & Forsaith, 1949) reported a couple of equations for determining the latent heat of vaporization as function of the temperature. The first equation is:

$$H = 596.73 - 0.601 \cdot T_c \qquad \text{(Eq. 2.4)}$$

where H is the latent of vaporization in calories per gram of water evaporated and T_c refers to the temperature in degrees Celsius at which the change takes place. The second equation reported by Brown et al. (1949) has the same structure but in this case the heat of vaporization (H) is expressed in BTU per pound of water evaporated and temperature (T_f) is in degrees Fahrenheit as follows:

$$H = 965.7 - 0.7 \cdot \left(T_f - 212\right) \qquad \text{(Eq. 2.5)}$$

The latent heat of vaporization can be also calculated from the Clausius Clapeyron equation in differential form which is stated as (adapted from Flowers and Mendoza 1970 as cited in Humphrey & Bolton, 1989):

$$H_L = 2.511\ x\ 10^6 - (2.48\ x\ 10^3) \cdot T \qquad \text{(Eq. 2.6)}$$

where H_L is the latent heat of water (J/kg H_2O) and T is the evaporation temperature (°C).

On the other hand, Weichert (1969 as cited in Simpson & Forest Products Laboratory, 1991) derived an experimental equation to determine the heat of sorption in the following way:

$$\Delta h_a = exp\left[-14.5 \cdot \left(\frac{M_i}{100}\right) + 6.18\right] \quad \text{(Eq. 2.7)}$$

where:

- ✓ Δh_a is the differential heat of sorption (BTU/lb H_2O)
- ✓ M_i is intermediate moisture content (%)

The differential heat of sorption may be also calculated from an expression similar to that determined by Bramhall (1979 as cited in Humphrey & Bolton, 1989). Such expression is:

$$H_W = 1.176\ x\ 10^6\ x\ e^{(-0.15 \cdot M)} \qquad \text{(Eq. 2.8)}$$

where H_W is the differential heat of desorption (J/kg H_2O) and M is moisture content of wood.

Skaar (1988) reported the following expression to estimate the differential heat of sorption in wood based on an empirical equation for textiles proposed by Cooper and Ashpole (1959 as cited in Skaar, 1988):

$$Q_s = 280 \cdot exp(-14 \cdot m) \quad \text{(Eq. 2.9)}$$

where Q_s is the differential heat of sorption in cal/g and m is moisture content in wood.

Siau (1995) also reported an expression to determine the heat of sorption based on equations reported by Skaar (1988) as follows:

$$Q_s = 1.17 \times 10^6 \cdot exp(-14 \cdot m) \quad \text{(Eq. 2.10)}$$

where Q_s is the differential heat of sorption in J/kg and m is a moisture content level below fiber saturation point.

Finally, the following expression proposed by Humphrey and Bolton (as cited in Thoemen & Humphrey, 2006) combines both the latent heat of evaporation and the differential heat of sorption:

$$H = 2.511 \times 10^6 - 2.48 \times 10^3 \cdot T + 1.172 \times 10^6 \cdot e^{-0.15 \cdot u} \qquad \text{(Eq. 2.11)}$$

where the heat energy required to evaporate a unit of bound water, H in J/kg, is expressed as a function of the temperature T in °C and moisture content u in %. It is important to point out that this expression to determine the heat required to produce a unit of vapor is the summation of the both previously mentioned Clausius Clapeyron equation to determine the latent heat of water and a similar equation to that of Bramhall to determine the differential heat of desorption for the water-wood system (Humphrey & Bolton, 1989)

2.3.1.3.2. Sensible heat

Sensible heat is the energy required to raise the temperature of the wood-water system to drying temperature. In the case of flue gas dryers, an important amount of energy is used to heat the biofuel – including its water – to the wet bulb temperature of the flue gas. In fact, the most common method to dry biofuels is to make use of the sensible heat of the flue gas (Wimmerstedt, 2007). Figure 2-15 illustrates how sensible heat varies as a function of moisture content. From Figure 2-15, it is quite clear how sensible heat significantly increases as moisture content and temperature rise.

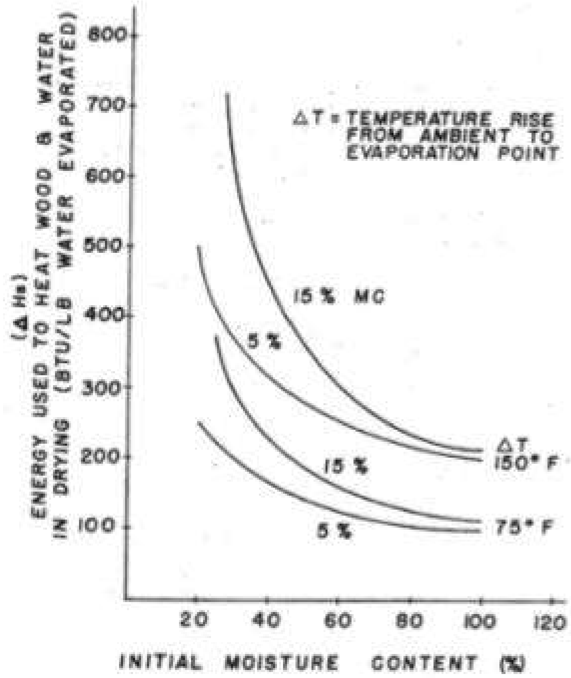

Figure 2-15: Variation of sensible heat as a function of initial moisture content (Comstock, 1975)

Mathematically, the sensible heating for drying of wood may be expressed as (Comstock, 1975):

$$\Delta H_S = \frac{\left(C_{wd} + \frac{M_i}{100} \cdot c_{wa}\right) \cdot \Delta T}{\left(\frac{\left(M_i - M_f\right)}{100}\right)} \qquad \text{(Eq. 2.12)}$$

or

$$\Delta H_S = \frac{(30 + M_i)}{M_i - M_f} \cdot \Delta T \quad \text{(Eq. 2.13)}$$

where:

- ✓ ΔH_S = sensible heat (BTU/lb of water evaporated)
- ✓ C_{wd} = specific heat of wood (BTU/lb°F)

- ✓ C_{wa} = specific heat of water (BTU/lb°F)
- ✓ M_i = initial moisture content (%)
- ✓ M_f = final moisture content (%)
- ✓ ΔT = temperature change from ambient to evaporation temperature (°F)

2.3.1.3.3. Heat losses

Heat lost through exhausting of air is also a major source of energy required for drying of wood products. Energy losses associated to exhausting of air is thought to be proportional to the temperature drop in the air as it passes through the dryer (Comstock, 1975). Heat losses due to exhausting of air may be a large or small proportion of the total amount of energy used in drying depending on the type of equipment. For example, vented energy may be less than 10% of the total energy in dryers where the proportion of air vented is small or the outlet temperature is near ambient while in non-recirculating particle dryers such losses may account up to 50% of the total energy (Comstock, 1975). The latter fact can be observed in Figure 2-16.

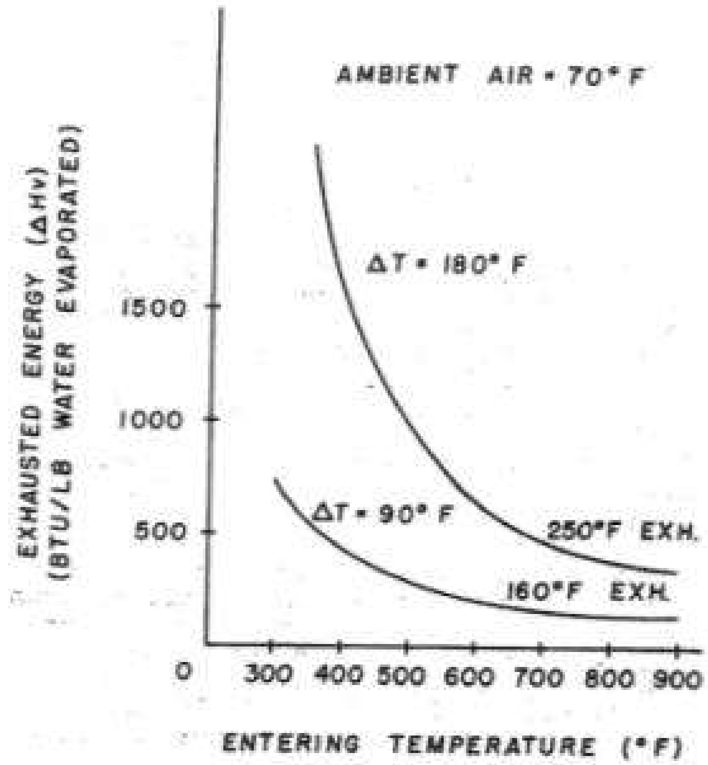

Figure 2-16: Energy exhausted to atmosphere in single pass particle dryer (Comstock, 1975)

A rough estimation of the amount of heat lost by exhausting of air can be obtained based on the ratio of vented energy to the minimum drying energy. Mathematically, such ratio is expressed as:

$$\frac{\Delta H_V}{\Delta H_{min}} = \frac{(T_L - T_A) \cdot X_v}{T_E - T_L} \qquad \text{(Eq. 2.14)}$$

where:

- ✓ ΔH_V = vented energy
- ✓ ΔH_{min} = minimum energy requirement for evaporation drying
- ✓ T_L = outlet temperature
- ✓ X_v = fraction of air vented

- ✓ T_A = ambient temperature
- ✓ T_E = inlet temperature

Blankernhorn and Weyers (1980) reported an equation to determine the energy requirements for a drying process as a function of the drying efficiency. The authors defined drying efficiency as follows:

$$Drying\ efficiency\ (\%) = 100 - \left(\frac{D - 2.79MJ/kg\ of\ water}{2.79MJ/kg\ of\ water}\right) \cdot 100 \qquad \text{(Eq. 2.15)}$$

where D is the drying energy used to remove 1 kg of water at a selected drying efficiency.

Additionally to the heat losses linked to exhausting of air, other sources of energy losses are related to dryer design, maintenance deficiencies, and heat to losses due convection and radiation from the dryer's walls. Nevertheless, since there are several sources of heat loss – some of them very difficult to calculate, actual energy values for drying will be somewhat above the calculated energy requirements.

2.3.2.3. Energy consumption for drying of wood particles

It would not be irrational to state that drying is likely the separation process with the highest energy consumption (Wimmerstedt, 1999). Based on the ideas that were previously discussed, several factors influence the amount of energy required to perform drying of wood. Thus, a review of the published literature provided an insight in the energy requirements for drying of wood particles.

Comstock (1975) reported that the energy required for drying of wood products vary in a range of 3 – 7 MJ/kg of water evaporated (1,300 – 3,000 BTU/lb of water evaporated).

Rosen (1995) rearranged information provided by Comstock (1975) and reported the following table for drying of particles in the production of particleboard:

Table 2-4: Range of approximate energy use for drying of particles (Rosen, 1995)

Type of particle	MC (%)		Energy use	
	Initial	Dry	MJ/kg H_20 (BTU/lb H_20)	MJ/m^3, 20 mm (MBTU/ft_2, 3/4 in)
Dry wood residues	25	5	4.7-7.0 (2,000-3,000)	490-760 (1.1-1.7)
Wet wood chips	100	5	3.7-5.1 (1,600-2,000)	1,900-2,320 (4.2-5.2)
Green chips	100	5	4.7-5.8 (2,000-2,500)	2,320-2,900 (5.2-6.5)

Thompson (1976) stated that by changing some drying condition – what the author defines as "special drying environments" – it becomes possible to reduce the energy consumption in a rotary dryer. The author said that by simply changing from high excess air conditions to a low air excess system and keeping the same ambient and material temperatures, energy requirements can change from above 4 MJ/kg H_2O (1700 BTU/lb H_2O) to 3 MJ/kg H_2O (1300 BTU/lb H_20). Similarly, Wimmerstedt (1999) stated that it is possible to have low energy use in a flue gas dryer by setting the drying conditions to optimum values. This is achieved by recirculating the drying gas and using high inlet gas temperatures (Wimmerstedt, 1999). According to Wimmerstedt, energy use of roughly 3.1 MJ/kg can be obtained when the gas dew point temperature and dry bulb temperature at the dryer exit are 80 °C and 110 °C, respectively.

Keeping the same idea about the effect of drying conditions on energy requirements, Malte et al (1977) analyzed the energy utilization for convection drying of wood particles in a straight drying tube. Two cases were studied: hot (649 °C (1200 °F) and 149 ° C (300 °F) for inlet and outlet temperatures, respectively) and cold (429 °C (800 °F) and 93 ° C (200 °F) for inlet and outlet temperatures, respectively). An energy balance showed that the input energy from the burner to dry 453 kg (100 lb) of dry particles was about 99 MJ (93,800 BTU) for the hot case while for the cold case was 79 MJ (74,900 BTU). After the experiments, Malte et al. concluded that the use of high particle velocity reduces the gas temperature while maintaining drying rates. As a result, net savings in drying input energy can be obtained.

As mentioned above, Blankernhorn and Weyers (1980) correlated energy requirements and drying efficiency. Based on a relatively simple mathematic expression, authors estimated energy requirements of 2.79, 4.19, and 5.58 MJ/kg H_20 for drying efficiencies of 100%, 50%, and 0%, respectively.

So far, values of energy requirements for drying of wood particles are associated to flue gas rotary dryers. This is due to the abundance of this type of equipment in the industry. Nonetheless, other types of drying equipment have been also analyzed from an energy perspective. For example, Wimmerstedt (1999) indicated that the typical gross energy use in a steam dryer is 2.9 MJ/kg – excluding leakage losses. However, it was also stated that such value is not very useful since it depends on several factors such as: inlet moisture content as well as inlet and outlet temperatures. Therefore, after accounting for the just mentioned variables, the net heat consumption required in steam drying process with normal heat recovery is around 4.6 MJ/kg.

Berghel (Berghel, 2002) determined the amount of heat energy required for drying sawdust and willow wood chips in a pilot-scale fluidized superheated atmospheric condition steam dryer. In the case of sawdust, the energy consumption was about 578 KJ/kg of water evaporated. On the other, the heat energy required for drying of willow wood chips was about 963 KJ/kg of water evaporated. Therefore, it is clear the effect of particle size and shape on energy requirements for a drying process.

Corder (1958) reported values for drying using suspension dryers. Total energy consumption was broken down into the different types of heat required for drying as is shown in Figure 2-17.

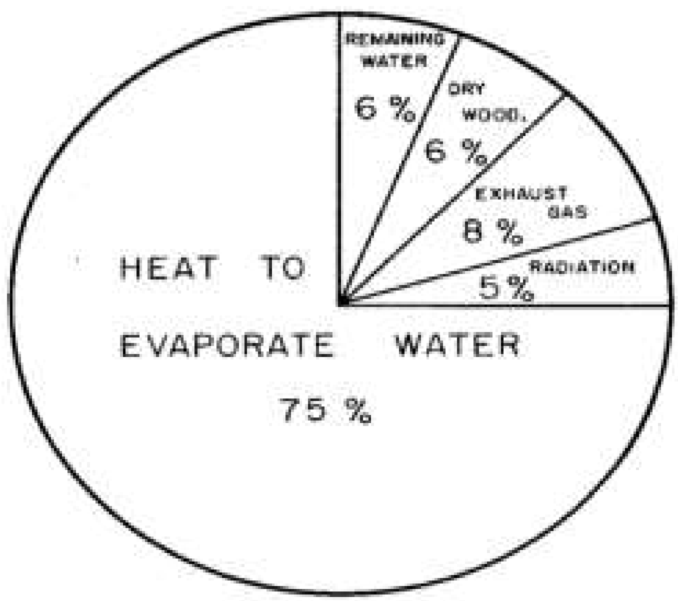

Figure 2-17: Heat balance for a suspension dryer (Corder, 1958)

Le Lostec et al. (Le Lostec, Galanis, Baribeault, & Millette, 2008) analyzed the drying process of wood chips using an absorption heat pump. The authors reported the amount energy required for drying of wood chips at different air temperatures and moisture content. Results are presented on Figure 2-18.

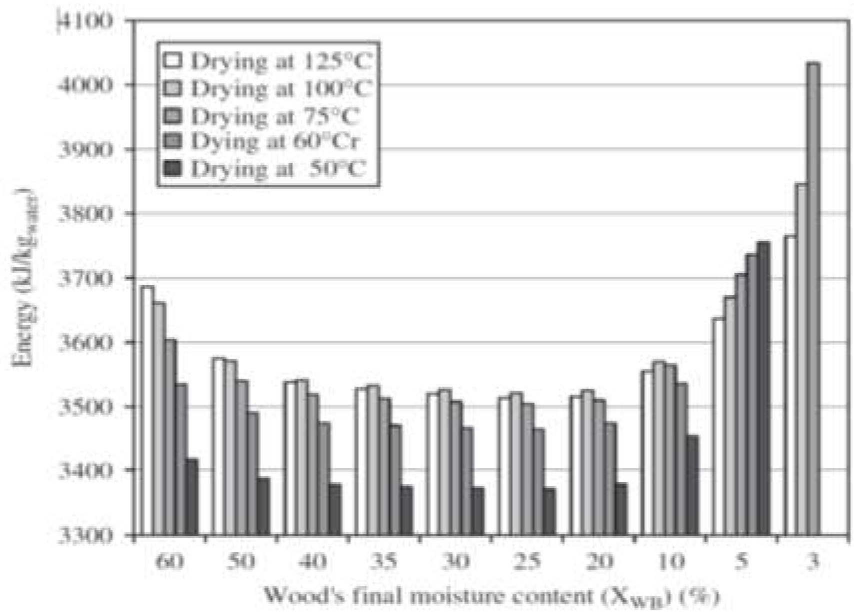

Figure 2-18: Specific energy required to dry wood chips (Le Lostec et al., 2008)

Thek and Obernberger (2004) stated that the heat demand for drying mainly depends on systems used for such operation. According to this study, energy requirements vary from 3.1 MJ/kg of evaporated water (865 kWh per tonne of evaporated water) for superheated steam dryers to 3.96 MJ/kg of evaporated water (1100 kWh / tonne of evaporated water) for belt dryers.

2.3.3. <u>Densification</u>

Densification refers to the single manufacturing process in which wood particles relatively uniform in size and moisture content are compacted by subjecting such particles to high temperature and pressure conditions.

There are several types of densification such as: piston press densification, screw press densification, roll press densification, pelletizing, and cubing. Products from piston press densification, screw press densification, and roll press densification are called briquettes (Bhattacharya, 1989). On the other hand, products obtained from pelletizing are called pellets.

Piston press densification (Figure 2-19) refers to the process in which a reciprocating piston (compacting ram) pushes the raw material against a tapered die (Bhattacharya, 1989). In the case of screw press densification (Figure 2-20), the raw material is conveyed and compressed by a screw (Bhattacharya, 1989). Roll press densification (Figure 2-21) refers to compaction of the raw material between the faces of roller bearing shaped cavities that rotate in opposite directions (Bhattacharya, 1989)(Reed & Bryant, 1978). In pelletizing (Figure 2-22), the pressure between the roller and the matrix plate that form a pelletizing press forces the raw material through perforations in the matrix plate (Bhattacharya, 1989). Finally, cubing is a modification of pelletizing in which the products are larger or cube shaped (Reed & Bryant, 1978).

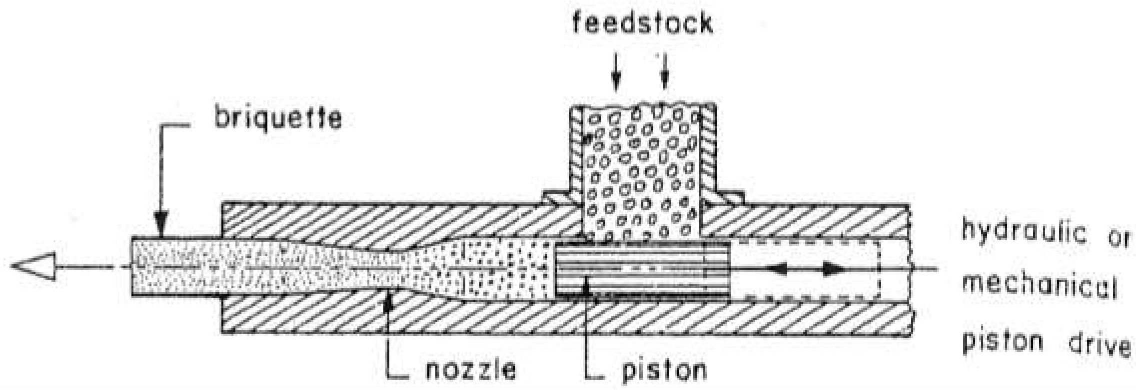

Figure 2-19: Piston press densification (Bhattacharya, 1989)

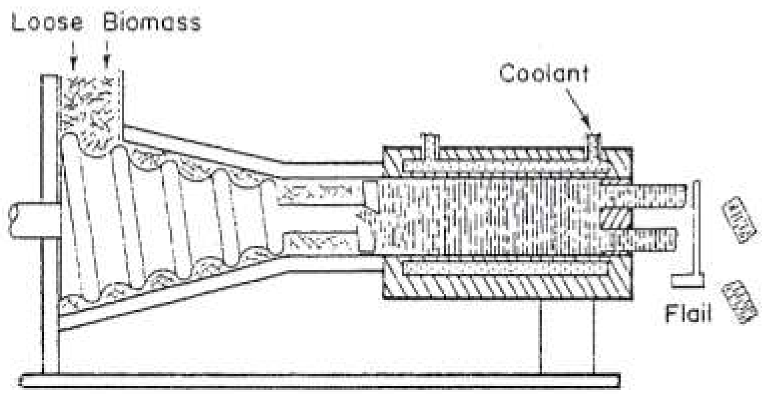

Figure 2-20: Screw press densification (Bhattacharya, 1989)

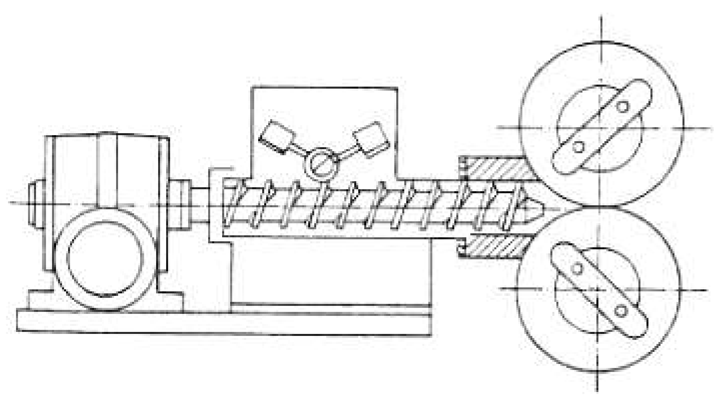

Figure 2-21: Piston press densification (Bhattacharya, 1989)

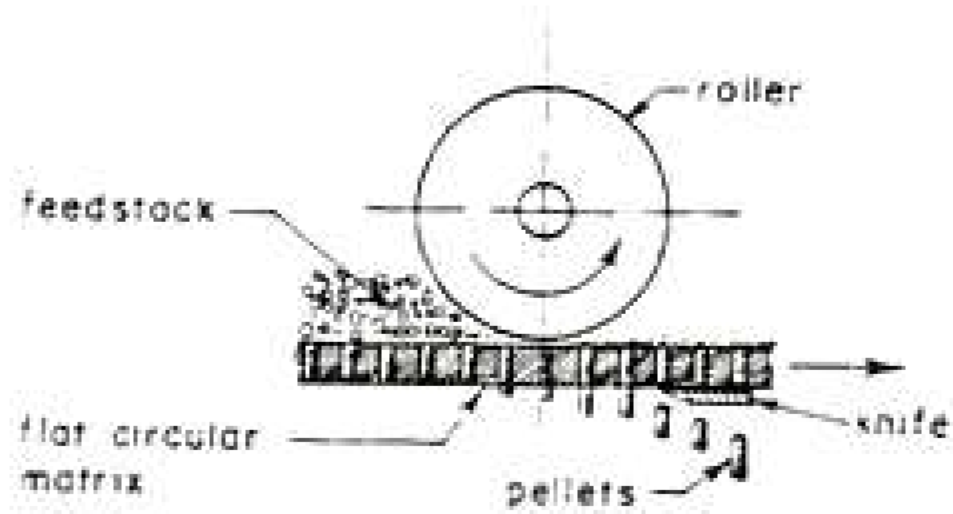

Figure 2-22: Piston press densification (Bhattacharya, 1989)

In the case of granular materials, such as wood, densification can be accomplished without the use of any binders since these materials are self-bonding when compacted at elevated temperatures (Reineke & Forest Products Laboratory, 1964). The binding mechanism of wood densification involves the combination of factors such as: adhesion and cohesion forces, attractive forces between solid particles, softened lignin, Var der Waals forces, and interlocking bonds (Pietsh 1991 as cited in Grover & Mishra, 1996) (Cattaneo, 2003). This binding mechanism can be explained in the following way. Small divided solids are able to attract atoms and free molecules from the surrounding atmosphere. As a result, the surfaces of these materials form absorption layers which cannot move freely anymore so they remain in close contact or penetrate each other. The lignin produced at high pressure and temperatures influences the layer absorption state. The application of high pressures increases the contact area which increases the strength of the bond between the adhering partners. Van der Waals forces also play an important role in this process – especially in powdered biomass – because they form further chemical bonds. In the case of bulky particles, they interlock or fold about each other to form interlocking or form-closed bonds. The final strength of the densified product depends upon the type of interaction and the characteristics of the material (Grover & Mishra, 1996)

2.3.3.1. Factors that affect densification processes and densified products

A number of factors have a significant bearing not only on the densification process but also on the properties of the densified products (Bhattacharya, 1989). Some of these factors are operational parameters linked to the densification process while other factors are related to the properties of the raw material. The following paragraphs discuss both types of variable.

2.3.2.1.1. Temperature and pressure

Several operational factors influence the densification processes as well as the products' properties. There is no doubt that temperature and pressure are two of the most important parameters of any densification process. First at all, when wood is subjected to high temperatures and pressures, lignin is softened and starts to act as internal glue during the densification process. Moreover, variation in the temperature of the material being densified affects density, compressive strength, and moisture stability of briquettes (Grover & Mishra, 1996). It has been reported that compressive strength of densified products increases as temperature rises. However, if temperature is raised too much, compressive strength of briquettes is negatively affected due to thermal degradation of at least one of the constituents of the biomass (Bhattacharya and Yeasmin 1984 as cited in Bhattacharya, 1989). Additionally, high temperature attained during the densification process may cause partial carbonization or torrification on the surface of the briquette making it resistant to moisture during storage (Grover & Mishra, 1996). The effect of compaction pressure on density of the final products is very significant. In fact, Li and Liu (2000) reported that the density of wood densified products increased with the compaction pressure.

2.3.2.1.2. Speed of compaction

Besides temperature and pressure, speed of compaction is another parameter affecting the properties of densified products. For example, density of compacted wood products tends to decrease as compaction speed increases (Li & Liu, 2000). However, there is certain point at which the effect of compaction speed on briquette density becomes negligible (Li & Liu, 2000).

2.3.2.1.3. Type of equipment

Additionally, the type of equipment used for densification is also a parameter to take into consideration when analyzing densification processes. For example, piston press densification is a batch-type process while screw press densification is continuous. Power consumption and maintenance costs linked to the screw press equipment are higher than that of piston press machines (Grover & Mishra, 1996). Briquettes produced using screw presses are partially pyrolyzed at the surface which provides easy ignition and combustion as well as protection from moisture (Grover & Mishra, 1996). Additionally, briquettes made on screw press have a hole along their length that improves air circulation during combustion (Grover

& Mishra, 1996). Roll presses require smaller particles than any other process and they are successful when a binder is used (Bhattacharya, 1989). Furthermore, products from roll presses are less durable than products from screw presses (Bhattacharya, 1989).

2.3.2.1.4. Moisture content

Moisture content is a critical variable to control during any densification process since it may affect both positively and negatively the process itself and the final products. For example, in the case of lignocellulosic material, the right amount of water develops self-bonding properties at elevated temperatures and pressures (Sen K.C. 1987 as cited in Grover & Mishra, 1996). Moreover, water helps promote bonding through Van der Walls' forces by increasing the particles contact area (Grover & Mishra, 1996). Water also facilitates the heat transfer during densification (Carre et al. 1987 as cited in Bhattacharya, 1989). It has been found that water in the raw material in necessary to induce flowability of lignin (Schaap 1985 as cited in Bhattacharya, 1989). Furthermore, if the moisture content is too low, the briquette surface will tend to crack as the briquette leaves the die (Karlhager, 2008). On the other hand, if moisture content is too high, it may form steam during compaction resulting in an explosion (Bhattacharya, 1989). Li and Liu (2000) reported that in the case of sawdust, moisture content levels above 13% resulted in densified products with low densities which disintegrated easily. The same study also showed that when the initial moisture content was below 4% products could not maintain good qualities for long. It is very difficult to determine the exact amount of water since it depends on several parameters such as the densification process, raw material properties, densification equipment, etc. In the case of wood, a moisture content ranging from 8 to 12 % is suitable for wood densification (Karlhager, 2008).

2.3.2.1.5. Particle size

Particle size and shape are essential for the success of biomass densification. It is believed that fine particles are easier to compact than larger ones. In fact, fine particles provide larger surface area which promotes bonding (Koullas and Koukios 1987 as cited in Bhattacharya, 1989). Additionally, it was found that throughput tends to increase as particle size decreases (Trezek et al. 1981 as cited in Bhattacharya, 1989). When larger particles are used as raw material for densified products, it is advantageous to add an adequate amount of small particles for embedding into the larger particles (Grover & Mishra, 1996). Nonetheless, it has been suggested to use different size particle since it improves the packing dynamics and the high static strength of the final products (Ludwing 1984 as cited in Grover & Mishra, 1996). In the case of wood, results from a study which analyzed the effect of three different wood particle shapes (sawdust, mulch, and chips) showed that mulch makes better briquettes than sawdust and that briquettes made out of wood chips had the lowest quality (Li & Liu, 2000). As rule of thumb, particles should not be larger than 25% of the diameter of the densified products (Bhattacharya, 1989).

2.3.2.1.6. Raw material

Several parameters associated to densification depend on the type of raw material being compacted. Wood species affect densification operations and their products. In fact, the chemical composition of wood may significantly change compaction mechanisms. It has been reported that as lignin and extractive content increased above 34%, pellet durability decreased (Bradfield and Levi 1984 as cited in Bhattacharya, 1989). The authors explained that the excess of noncrystalline wood polymers – which act as mastic – reduces strength and durability of pellets. Additionally, the hemicelluloses fraction may also affect durability and strength of pellets (Bradfield and Levi 1984 as cited in Bhattacharya, 1989). On the other hand, Li and Liu (Li & Liu, 2000) reported that bark is easier to compact than wood, and hardwood is easier to compact than softwood.

2.3.3.2. <u>Energy consumption for densification of woody biomass</u>

It has been discussed that several factors affect densification processes as well as properties of densified products. Thus, it is not surprising that many of the factors mentioned above have a bearing on the energy requirements associated with biomass densification. In fact, energy requirements during biomass densification depend primarily on compaction pressure and moisture content of the raw material being densified (Mani, 2006). In the same way, physical properties of the raw material such as: bulk density, particle size, temperature, etc. also affect energy requirements for biomass densification (Mani, 2006). Additionally, the type of equipment used for biomass densification is a major parameter to take into consideration when analyzing energy requirements. For these reasons, the following paragraphs are intended to mention previous studies in which the relationship between energy requirements and variables associated to densification processes were analyzed.

Reed et al. (1980) reported that work and compaction pressure can be reduced by a factor of two by preheating the feedstock to 200-225 °C prior to densification. This preheating stage also brings other benefits along such as: lower electric power costs, lower equipment costs, reduced die wear, increase fuel value, and improved lubricity of the biomass. Reed et al. (1980) concluded that energy requirements for both extrusion and compression are reduced by a factor of about two if temperature is risen from room temperature to 225 °C. Furthermore, the authors agreed that even though their results – obtained in a laboratory – are lower than those of commercial equipment, they can be comparable.

Aqa and Bhattacharya (1992) stated that the energy input required for sawdust briquetting is reduced significantly when the material temperature is high. For example, at a sawdust temperature of 100 °C and a die temperature of 250 °C, the electrical energy input was roughly 0.48 MJ/kg (134 kWh per ton) of sawdust while at a sawdust temperature of 115 °C and a die temperature of 300 °C, the electrical energy input was about 0.39 MJ/kg (107 kWh per ton) of sawdust. The authors explained that if the raw material is preheated prior to briquetting, the lignin is already soft by the time it is fed into the machine which results in lower force and energy requirements for compaction. Moreover, it was reported that preheating also increases throughput capacity of the densification equipment which reduces the electrical energy requirement per ton of sawdust.

CHAPTER 3

METHODOLOGY

A full factorial model was used to construct the design of experiments (DOE) for this project. Due to the nature of this project, the experimental design was divided into two parts. The first part of the experimental design focused on the size reduction stage for the production of wood briquettes. Four factors were considered to develop this part of the experimental design: wood species, initial condition of the raw material (lumber) for primary size reduction, particle size obtained from primary size reduction, and secondary size reduction. Wood species were examined at three levels: eastern white pine (*Pinus strobus*), southern yellow pine (*Pinus spp.*) and yellow poplar (*Liriodendron tulipifera*). The initial condition of the raw material (lumber) for primary size reduction was analyzed at two levels green lumber and kiln-dried lumber. The particle size of the material obtained from primary size reduction was studied at two levels: wood chips from 12 to 15 mm in size and wood chips from 15 to 20 mm in size. Secondary size reduction (hammermilling) was evaluated whether it was performed or not (two levels). Table 3-1 summarizes the arrangement of factors and levels of the experimental design. 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 size reduction of wood.

Table 3-1: Experimental design for size reduction

Wood species	Initial condition of raw material for primary size reduction	Particle size obtained from primary size reduction	Secondary size reduction
Eastern white pine	Dry	**12 – 15 mm**	No Yes
		15 – 20 mm	No Yes
	Wet	**12 – 15 mm**	No Yes
		15 – 20 mm	No Yes
Southern yellow pine	Dry	**12 – 15 mm**	No Yes
		15 – 20 mm	No Yes
	Wet	**12 – 15 mm**	No Yes
		15 – 20 mm	No Yes
Yellow poplar	Dry	**12 – 15 mm**	No Yes
		15 – 20 mm	No Yes
	Wet	**12 – 15 mm**	No Yes
		15 – 20 mm	No Yes

The second part of the experimental design for this project is concentrated on the densification stage for the production of wood briquettes. Three factors: wood species, initial condition of the raw material before primary size reduction, and particle size for densification. Three wood species were evaluated: eastern white pine (*Pinus strobus*), southern yellow pine (*Pinus spp.*) and yellow poplar (*Liriodendron tulipifera*). The initial condition of the raw material before primary size reduction was studied at two levels: green lumber and kiln-dried lumber. The particle size prior densification was analyzed at two levels: 3 mm (after hammermilling) and 12 – 15 mm (after shredding). Table 3-2 shows the arrangement of factors and levels of the experimental design. Three replicates for each treatment were tested and the average of these replicates was used as a final result. The response parameters evaluated in this part of the experimental design were energy consumption for densification of wood chips and energy density of the briquettes.

Table 3-2: Experimental design for densification

Wood species	Initial condition of raw material before primary size reduction	Particle size for densification
Eastern white pine	Dry	3 mm
		12 – 15 mm
	Wet	3 mm
		12 – 15 mm
Southern yellow pine	Dry	3 mm
		12 – 15 mm
	Wet	3 mm
		12 – 15 mm
Yellow poplar	Dry	3 mm
		12 – 15 mm
	Wet	3 mm
		12 – 15 mm

3.1. Materials and Methods

Three different wood species were considered in this experimentation (Figure 3-1): eastern white pine (*Pinus strobus*), southern yellow pine (*Pinus spp.*) and yellow poplar (*Liriodendron tulipifera*). Wood was obtained as lumber and sorted by species and moisture content (green lumber and kiln-dried lumber). Green eastern white pine lumber was donated by Bryant & Young Lumber Company, Burnsville, NC. Kiln-dried eastern white pine was obtained from a national home improvement store (Lowe's, Cary, NC). Green and kiln-dried southern yellow pine lumber was donated by Lampe & Malphrus Lumber Company, Smithfield, NC. Green poplar lumber was donated by Edwards Wood Products, Liberty, NC. Kiln-dried poplar lumber was donated by Jerry G. Williams and Sons Lumber Company, Smithfield, NC. Moisture content of lumber was determined using Delmorst Instrument Company RDM-2 pin-type moisture meter. Three moisture content measurements were taken lengthwise in order to calculate the average moisture content of the board

Eastern white pine (*Pinus strobus*)

Southern yellow pine (*Pinus spp*)

Yellow poplar (*Liriodendron tulipifera*)

Figure 3-1: Wood species considered in the experimentation

3.1.1. <u>Size reduction</u>

The equipment employed 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 (Figure 3-2) was used for size reduction of green and kiln dried pieces of lumber (19 mm x 38 mm x 1219 mm) into wood chips of 12 – 15 mm or 15 – 20 mm. Pieces of lumber were individually placed and aligned on the shredder's vibrating conveyor in such a way that the cutting knives on the shredding rotor were symmetrically distributed along the width of lumber piece. This comminution operation was called primary size reduction.

Figure 3-2: Weima horizontal shredder (http://www.weimaamerica.com/)

A C.S Bell Company 10HBML rotary hammermil (Figure 3-3) was utilized for size reduction of chips obtained from the horizontal shredder into 3 mm wood particles. Chips were gradually dropped on the hammermill's chute so gravity and vibration conveyed the chips inside the milling chamber. Based on preliminary experimentation, the hammermill could only process dry material. For this reason, chips obtained from shredding of green lumber were air dried prior to size reduction in the hammermill. This comminution process was labeled as secondary size reduction

Figure 3-3: C.S Bell rotary hammermill (http://www.csbellco.com/)

Moisture content of wood chips and particles was determined by oven drying following the ASTM E 871 as a guideline (American Society for Testing and Materials (ASTM), 2006).

3.1.2. 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. Such wood chips were laid out on the floor forming thin layer of chips for a period of 5-7 days (Figure 3-4). Indoor conditions in Hodges laboratory were around 15 - 21 °C (60 - 70 °F) and 40 – 50 % relative humidity. Moisture content of chips was determined by oven drying using the ASTM E 871 as a guideline (American Society for Testing and Materials (ASTM), 2006). Chips obtained from size reduction of kiln-dried lumber did not require air drying but equilibrated to the laboratory conditions.

Figure 3-4: Air-drying of wood chips

3.1.3. Densification

Densification of wood chips obtained from the shredder and wood particles processed on the hammermill were compacted using a Weima TH514 piston briquetting press (Figure 3-5). Wood chips and particles were dropped in the hopper of the briquetting press. Then, an auger moved the chips inside the compacting chamber. Finally, a ram compressed the chips to form the briquettes.

Figure 3-5: Weima horizontal shredder (http://www.weimaamerica.com/)

3.1.4. Determination of 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:

$$\text{Energy consumption} = \text{Power consumption x Processing period} \qquad \text{(Eq. 3.1)}$$

In equation 3.1, power consumption refers to the rate at which electrical energy is transferred and processing period is the time that takes to completely process (comminute or compact) a specific amount of wood (lumber, chips, or particles). Energy consumption, power consumption, and processing period are expressed in Joules (J), Watts (W), and seconds (sec) 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 Load Controls Inc. UPC power cell was attached to the electric system of the equipment (shredder, hammermill, or briquetting press) to monitor the load changes (power demand) on such equipment. Then, the power cell sends a signal with the power demand measurements to a computer. This signal is sent to the computer through a National Instruments BNC-2110 connector block and a National Instruments DAQCard-6024E acquisition card. Finally, graphical programming software (LabVIEW, version 8.2 from National Instruments) converted, displayed, and recorded the signal sent by the power cell. A Load Controls Inc. DM-100 load meter was also connected to the power cell to display real time power consumption. Figure 3-6 illustrates the set-up of the components employed for data acquisition.

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

$$\mathrm{H} = 2.511 \times 10^{6} - 2.48 \times 10^{3} \cdot \mathrm{T} + 1.172 \times 10^{6} \cdot \mathrm{e}^{-0.15 \cdot \mathrm{u}} \qquad \text{(Eq. 2.11)}$$

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

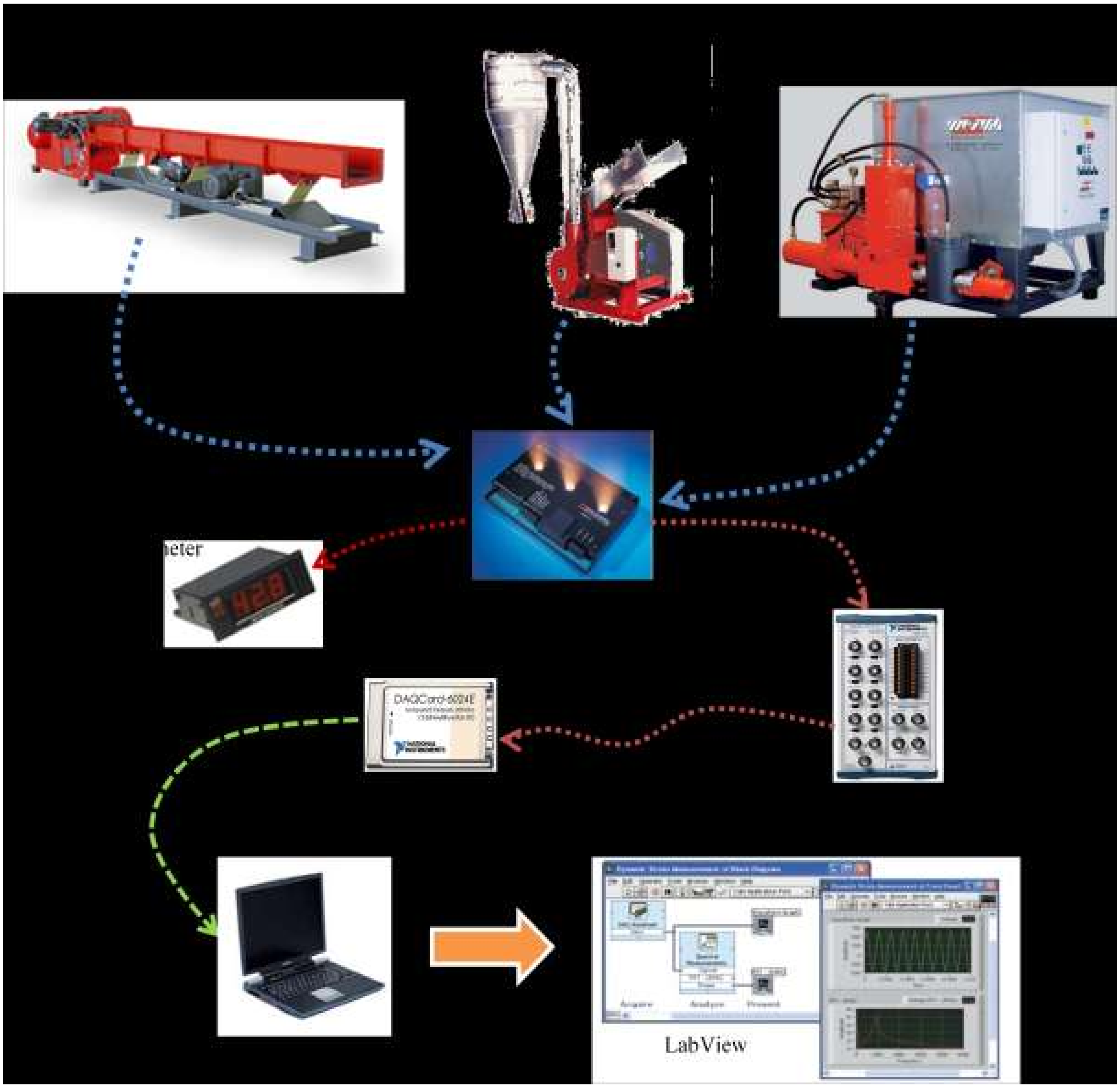

Figure 3-6: Data acquisition system

3.1.5. Determination of calorific values of briquettes:

The gross calorific value of briquettes was determined using a Parr Instrument Company 1341 oxygen bomb calorimeter (Figure 3-7) and following the procedure provided by the equipment manufacturer (Parr Instrument Company, 2008). Chips samples from the different species evaluated in this experimentation were ground down into powder using a Willey grinder equipped with a 20 mesh screen. Ground samples were compressed into pellets of 0.3 – 0.7 g using a Perkin Elmer Corporation press. Pellets were placed in the fuel capsule. A nickel chromium fuse wire was attached to the bomb electrodes. One milliliter (mL) of distilled water was added to in the bottom of the bomb as a sequestering agent and absorbent. Once the bomb was closed, it was filled with oxygen at 30 atm.

Figure 3-7: Parr oxygen bomb calorimeter (http://www.parrinst.com/)

The bomb calorimeter was submerged in the calorimeter bucket filled with 2000 (+/- 0.5) grams of distilled water. Equilibrium was reached by means of a power transmission system (motor-pulley) which stirred the water for a period of five minutes. At the end of this period, time and temperature were recorded using the timer of a 6775 Digital Thermometer. Then, temperature was recorded at one-minute intervals for five minutes. At the start of the 6^{th} minute, the bomb was fired (ignition). After ignition, temperature was recorded 45, 60, 75, 90, and 105 seconds after firing in order to measure the time required to reach 60 percent of the total temperature rise. After that (about 4 or 5 minutes after ignition), temperature was recorded at one minute intervals until the difference between successive readings has been constant for five minutes. Subsequently, the bomb was removed from the calorimeter bucket. All interior surfaces of the bomb were washed with jet of distilled water. Washings were collected and titrated with a standard sodium carbonate solution using methyl orange or methyl red indicator. All unburned pieces of fuse wire were removed from the bomb electrodes and measured in order to determine the net amount of wire burned. Finally, the gross calorific value of the samples was determined by the following equation provided by the equipment manufacturer (Parr Instrument Company, 2008):

$$H_g = \frac{t x W - e_1 - 2.3 x e_3}{m} \quad \text{(Eq. 3.2)}$$

where:

H_g = gross calorific value in calories per gram

W = energy equivalent of the calorimeter, determined under standardization

e_1 = correction in calories for heat of formation of nitric acid (HNO_3) = c_1 if 0.0709N alkali was used for the titration.

c_1 = milliliters of standard alkali solution used in the acid titration

e_3 = correction in calories for heat of combustion of fuse wire = (2.3) x (c_3) when using nickel chromium fuse wire.

c_3 = centimeters of fuse wire consumed in firing

m = mass of sample in grams

t = temperature rise which is computed from:

$$t = t_c - t_a - r_1 x(b - a) - r_2 x(c - b) \qquad \text{(Eq. 3.3)}$$

a = time of firing

b = time (to nearest 0.1 min) when the temperature reaches 60 % of the total rise

c = time at beginning of period (after the temperature rise) in which the rate of temperature change has become constant

t_a = temperature at time of firing

t_c = temperature at time c

r_1 = rate (temperature units per minute) at which the temperature was rising during the 5-minute period before firing

r_2 = rate (temperature units per minute) at which the temperature was rising during the 5-minute period after time c. If the temperature was falling instead of rising after time c, r is negative and the quantity - r x (c-b) becomes positive and must be added when computing the corrected temperature rise

The net calorific value of briquettes was determined from the following equation provided by the bomb calorimeter manufacturer (Parr Instrument Company, 2008):

$$H_n = 1.8x\, H_g - 91.23x\, H \qquad \text{(Eq. 3.4)}$$

where, H_n represents the net calorific value (Btu/lb), H_g refers to the gross calorific value previously determined using a bomb calorimeter (Btu/lb), and H stands for the percentage of hydrogen in the sample.

The energy equivalent of the calorimeter was determined under standardization using one-gram benzoic acid pellets. The procedure for a standardization test is exactly the same as the one mentioned above. Four standardization tests were carried out from which an average was determine the true W value for the calorimeter. The energy equivalent of the calorimeter is calculated by substituting in the following equation (Parr Instrument Company, 2008):

$$W = \frac{Hxm - e_1 + e_3}{t} \qquad \text{(Eq. 3.5)}$$

H = heat of combustion of the standard benzoic acid sample in calories per gram

m = mass of the standard benzoic acid sample in grams

t = net corrected temperature rise in ° C

e_1 = correction for heat of formation of nitric acid in calories

e_3 = correction for heat of combustion of the firing wire in calories.

3.1.6. Determination of hydrogen content in wood samples

Hydrogen content of wood samples was determined in order to compute their net calorific value. A 2400 CHN Elemental Analyzer from Perkin Elmer Corporation was used to analyze the samples. The analyzer took a known weight of sample (8 mg) and combusts it in a pure O_2 environment. The resultant gases were passed through several chemicals (Silver Vanadate, Silver Tungstate on Magnesium Oxide, and Silver Oxide/Silver Tungstate in the combustion tube; and Copper and Copper oxide in the reduction tube) to eliminate unwanted gases and to convert all the forms of H into H_2O (and likewise C into CO_2). The gas was then mixed and passed through a detector column. After which the results were calculated and printed out. The instrument was based on the Dumas and Pregal methods.

3.1.7. Determination of the energy density of briquettes

The energy density of briquettes was mathematically calculated based on their net calorific value and density in the following way:

$$\text{Energy density} = \text{Net calorific value} \times \text{Density} \qquad \text{(Eq. 3.6)}$$

where energy density, net calorific value, and density were expressed in MJ/m^3, MJ/kg, and kg/m^3 respectively.

As mentioned above, the net calorific value of briquettes was determined using Equation 3.5. On the other hand, density of briquettes was calculated by recording the weight and volume of each briquette. Weight of the briquettes was determined using a digital scale while volume was obtained measuring their height and diameter.

3.2. Preliminary Experimentation

The main objective of the preliminary experimentation was to identify, define, and understand the most important parameters to be analyzed within this research. Moreover, this preliminary experimentation was used for defining methods to monitor, measure, and control the parameters being studied.

3.2.1. Analysis of power consumption and processing period during wood size reduction and densification

Based on Equation 3.1, power consumption and processing period were necessary variables to calculate energy consumption for size reduction and densification of wood. For this reason, power consumption of the size reduction and densification equipment was monitored using the data acquisition system described above.

Figure 3-8 illustrates power consumption of the Weima horizontal shredder (Y axis) over time (X axis). The left side of the chart (time = 0 – 3.5 s) shows power consumption of the shredder when it is running idle. At 3.5 s, power consumption suddenly increases. At this moment, the workpiece (piece of lumber) made contact with the shredding rotor. This point represents the start of the size reduction process. Power consumption during size reduction was more erratic than at idle due to intermittent impact of the cutting knives on the wood. Once the piece of lumber was completely processed, power consumption felt back to idle (time = 8.5 s). This point indicated the end of the size reduction process. The area between the start and the end of the size reduction process was defined as the shredding region (Figure 3-8). Processing period was defined as the length (in time) of the shredding region. It is important to mention that in order to determine the actual power consumption for processing of wood (net power consumption) it was necessary to subtract the power consumption when the shredder was at idle from the power consumption when the shredder was processing material. Several researchers have taken the same approach to determine the net power consumption during size reduction of biomass (Mani, Tabil, & Sokhansanj, 2004); (Holtzapple et al., 1989)

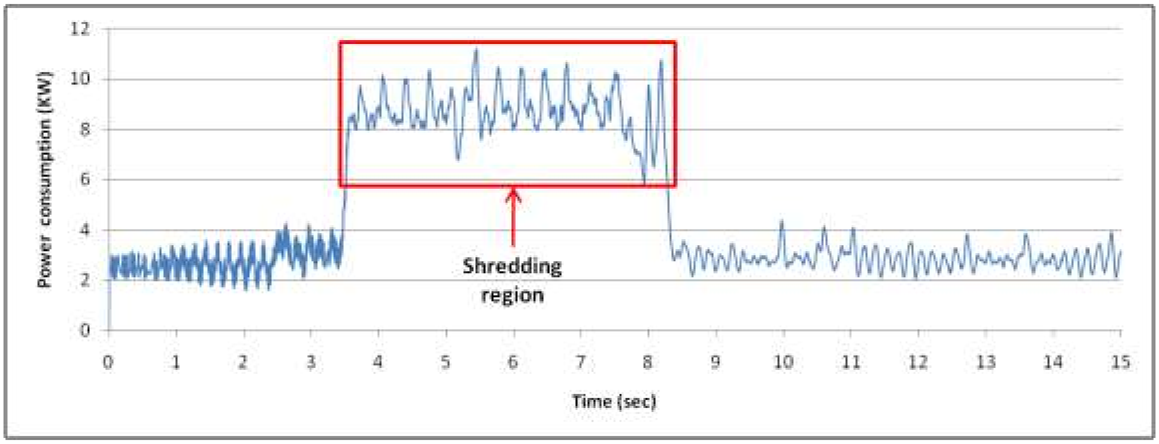

Figure 3-8: Power consumption of the Weima horizontal shredder

Power consumption of the C.S. Bell rotary hammermill (Y axis) over time (X axis) is presented in Figure 3-9. The chart started showing a power consumption of roughly 0.7 KW which represented the hammermill's idle state. Power consumption increased as wood chips get inside the milling chamber and start being hit by the hammers. This point indicated the beginning of the size reduction process. From this point, power consumption was erratic and irregular due to the inconsistency in the feeding of wood chips and the intermittent hitting action of the hammers on the chips. Inconsistency in the feeding of chips was caused by the lack of a feeding mechanism on the hammermill to feed chips at a constant rate. As a result, power consumption repeatedly drops and rises during hammermilling. Moreover, it also made the hammermill run nearly idle when it actually should be processing wood. This can be observed at time 350 and 550 seconds. Furthermore, chips tended to bundle themselves along the hammermill chute which made feeding even more inconsistent. When wood chips were completely processed, power consumption started dropping down to the idle state. Hammermilling was finished when the hammermill was idle (time equals 800 s). Similar to the horizontal shredder, the starting and finishing points of the size reduction process in the hammermill defined the hammermilling region. Processing period was defined as the length (in time) of the hammermilling region. Again, power consumption when the hammermill was running idle was subtracted from the power consumption when the hammermilling was processing wood chips in order to determine the net power consumption for processing of wood.

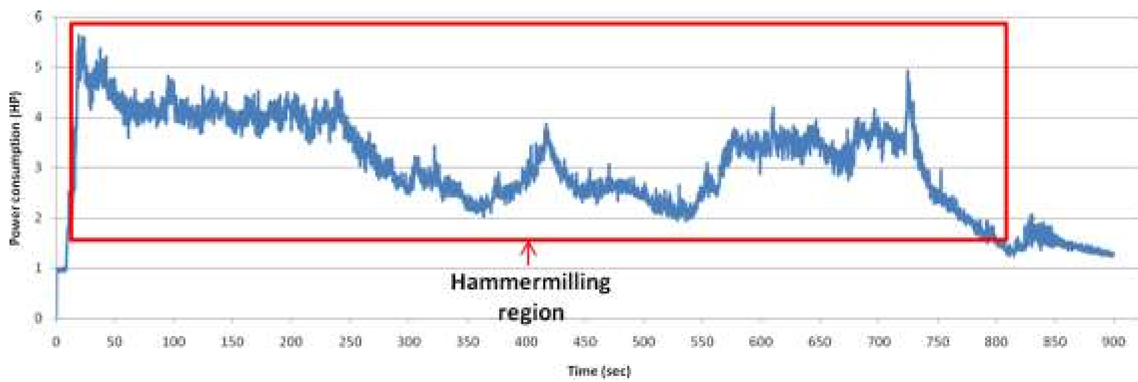

Figure 3-9: Power consumption of the C.S Bell rotary hammermill

Further experimentation regarding power consumption of the hammermill showed that the lack of an efficient feeding mechanism may overload the equipment causing it abruptly to shut down. In other words, since there was not a device or mechanism controlling the material feeding, the amount of chips falling in the milling chamber may surpass the maximum material processing capacity of the equipment which made the hammermill shut down. Experimentation showed the hammermill shut down due to overloading when power consumption reaches a cut-off value of roughly 3.5 KW for a prolonged period of time (Figure 3-10).

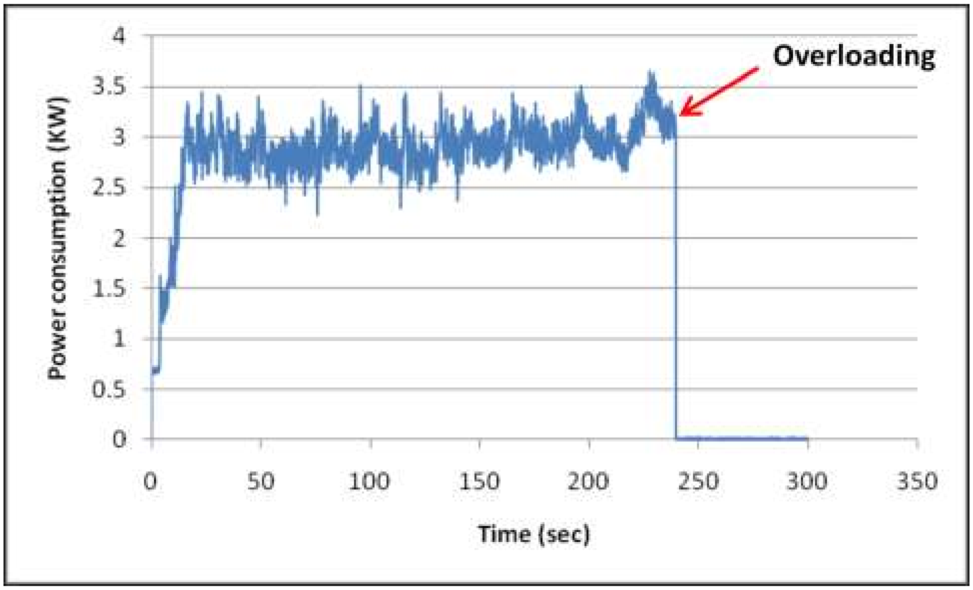

Figure 3-10: Overloading of the C.S Bell rotary hammermill

In order to deal with a potential overloading of the equipment caused by the inefficient feeding of chips, it was decided to drop the chips on the hammermill chute based on real-time power consumption values displayed by the load meter (Figure 3-6) so the cut-off value could be avoided. In addition, feeding the hammermill under this approach helped avoid both chips bundling on the hammermill chute (a cause of overloading) and idle running in the middle of the hammermilling operation (Figure 3-11).

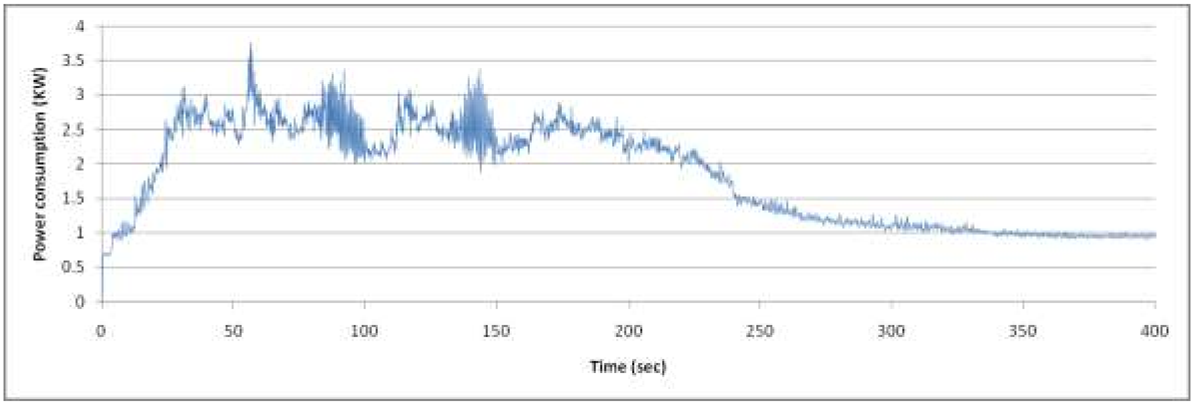

Figure 3-11: Power consumption of the C.S. Bell rotary hammermilling when wood chips were fed based on real-time power consumption values

Figure 3-12 shows a chart of the power consumption of the Weima briquetting press (Y axis) over time (X axis). The chart began with a very steady and constant power consumption which represented the idle condition of the briquetting press. At time = 4 s, power consumption suddenly increased which indicated the start of the compaction process. At this point, power was required for: moving the material into the compaction chamber, prepressing the material inside the compaction chamber with the load pusher, pressing the material to form the briquettes, and discharging the briquettes (Figure 3-13). At time = 7 s, power consumption dropped and the press started running idle again. This cycle repeated continuously until there was no material in the hopper. The area between the start and the end of each compacting cycle was defined as the compacting region (Figure 3-12). Processing period was defined as the length (in time) of the compaction region. In order to determine the actual power consumption for compacting of wood (net power consumption) was necessary to subtract the power consumption when the press is running idle from the power consumption when the press was compacting material.

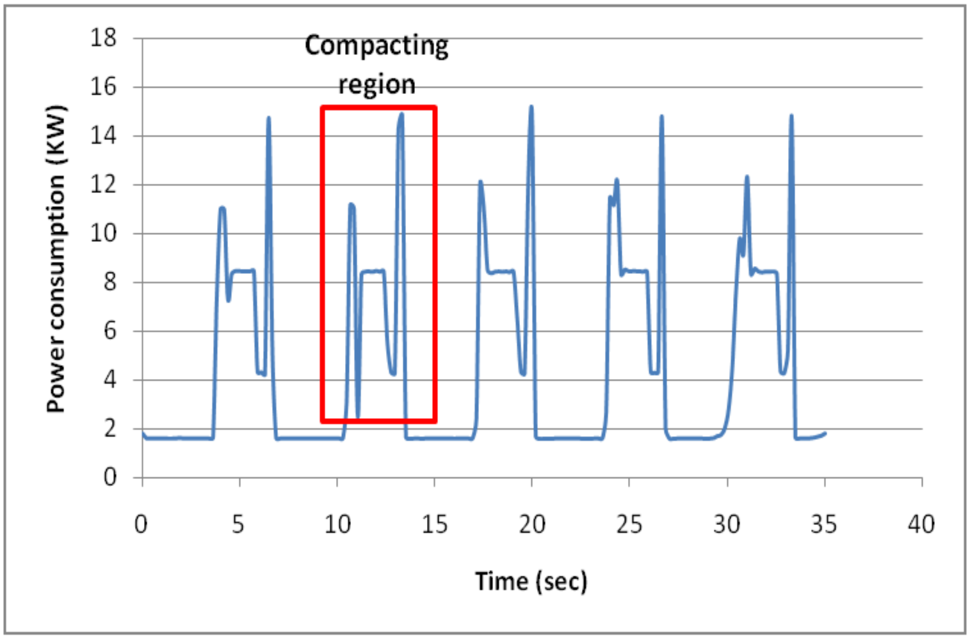

Figure 3-12: Power consumption of the Weima briquetting press

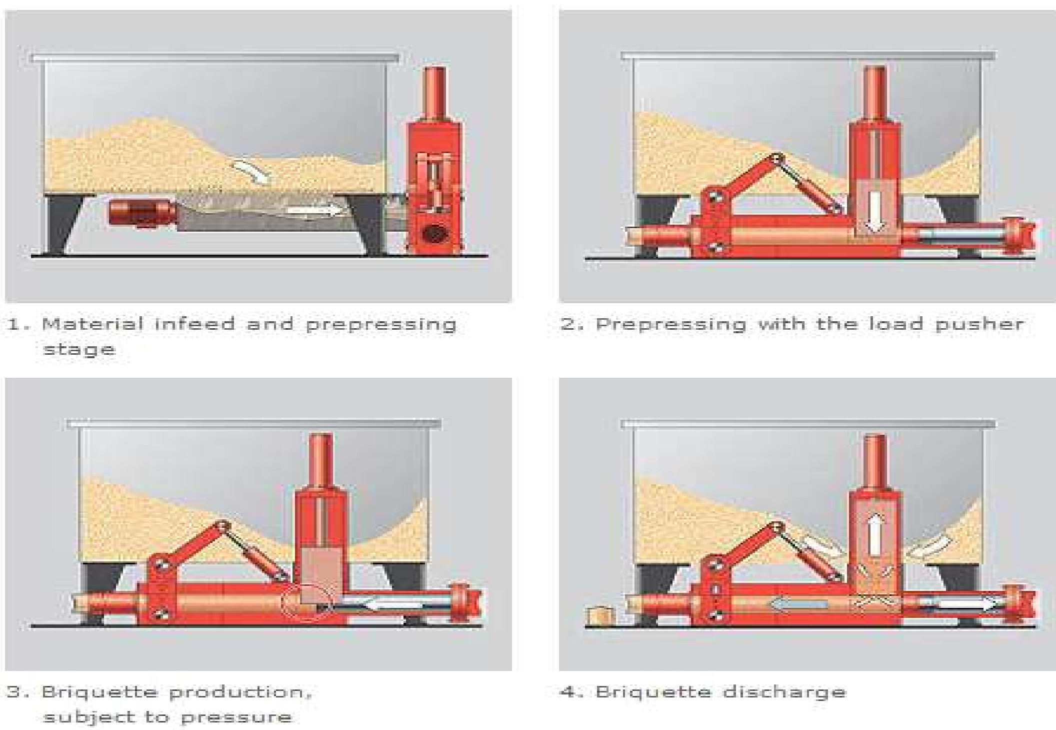

Figure 3-13: Operation of the Weima briquetting press

3.2.2. Definition of the dimensions of the samples to be processed on the horizontal shredder

The objective of this preliminary experimentation was to define the dimensions of the pieces of lumber to be processed on the horizontal shredder in the final experimentation. For this reason, a series of experiments were carried out to study the effect of processing pieces of lumber of different dimensions on energy requirements for size reduction of wood on the horizontal shredder. Lumber length, width, and thickness were studied independently along the experiments.

3.2.2.1. Lumber length

Three different lumber lengths were analyzed in this experiment: 1.2 m (4 ft), 2.4 m (8 ft), and 3.6 m (12 ft). Lumber cross- section dimensions were 19 mm x 89 mm (1 in x 4 in nominal). Samples were made out of kiln dried southern yellow pine lumber (*Pinus spp.*).

Results of this experiment are shown on Figure 3-14. It seemed that as lumber length increased so did energy requirements for size reduction on the shredder. However, difference in energy requirements for shredding of lumber samples with different lengths may be considered negligible. In fact, two statistical tests for means comparison (Tukey-Kramer HSD test and non-parametric Kruskal-Wallis test) showed there was no significant difference in energy consumption for shredding of lumber samples with different lengths. Both tests were performed using JMP® version 8 from SAS®. Details of the statistical tests are presented on Table A 1 of the appendices. Therefore, since there was no major difference in energy requirements for shredding of samples with different lengths, it was decided to use samples with length of 1.2 m (4 ft) for the final experimentation.

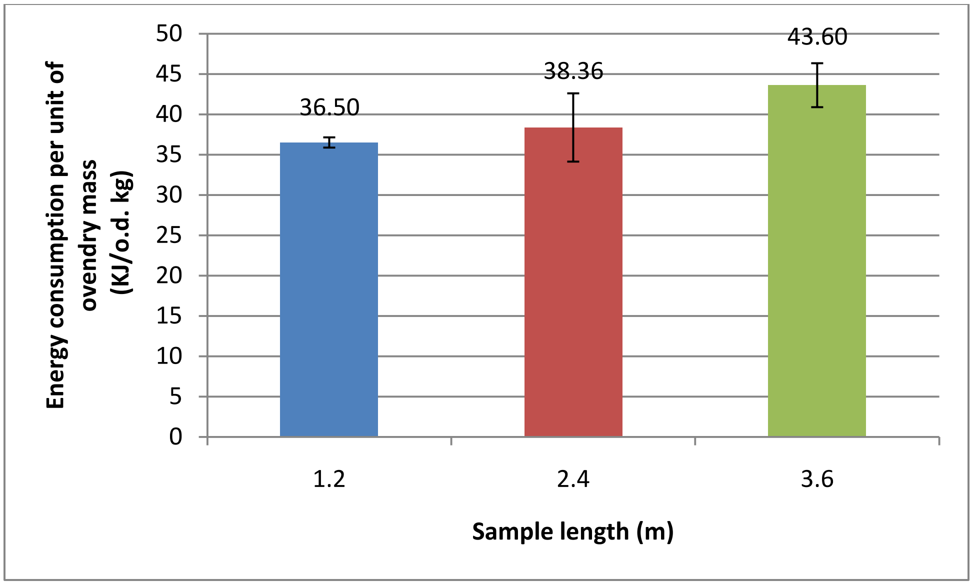

Figure 3-14: Energy consumption for shredding of pieces of lumber with different lengths (Each error bar is constructed using 1 standard deviation from the sample)

3.2.2.2. Lumber width

For this experiment, three different lumber widths were evaluated: 38 mm (2 in nominal), 89 mm (4 in nominal), and 140 m (6 in nominal). Samples thickness and length were 19 mm (1 inch nominal) and 1.2 m (48 inches), respectively. Samples were made out of kiln dried eastern white pine (*Pinus strobus*).

Figure 3-15 illustrates results obtained in this experiment. The results showed that energy requirements for shredding of wood seemed to increase as lumber width decreased. However, statistical tests for means comparison (Tukey-Kramer HSD test and non-parametric Kruskal-Wallis test) showed that there was no significant difference between the energy consumption for shredding of 89 and 140 mm wide lumber samples. Moreover, both tests also agreed that energy requirements for shredding of 38 mm wide samples were higher than those associated with 89 and 140 mm wide samples. Both statistical tests were performed using JMP® version 8 from SAS®. Details of the statistical tests are presented on Table A 2 in the appendices.

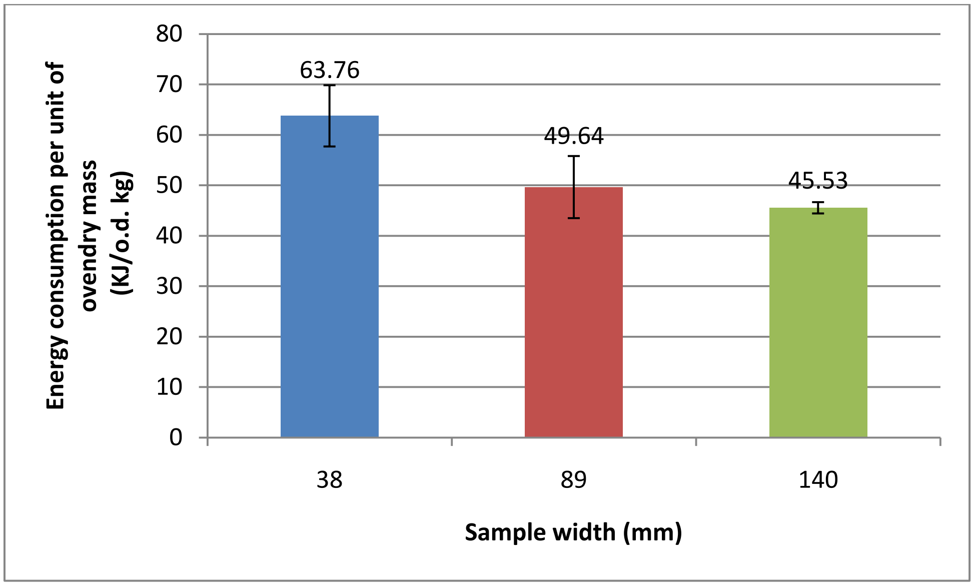

Figure 3-15: Energy consumption for shredding of pieces of lumber with different widths (Each error bar is constructed using 1 standard deviation from the sample)

In order to explain these results, it was necessary to return to the equation used in this experimentation to calculate energy requirements for shredding of wood (Equation 3.1). According to Equation 3.1, energy requirements for size reduction were directly proportional to both power consumption and processing period. So, for further analysis, let one assume the size reduction of one kg pieces of lumber of different widths (38 mm, 89 mm, and 140 mm) but same thickness (19 mm). Length of such lumber pieces would vary such that wider pieces would be shorter than narrower pieces. As a result, power consumption for size reduction of wider pieces would be higher than for size reduction of narrower pieces (Figure

3.16). This was due to the fact that the number of cutting teeth making contact with the lumber was higher for size reduction of wider pieces than for size reduction of narrower pieces (Figure 3-17). On the other hand, it would take longer to process narrower pieces than wider pieces because narrower pieces were longer than wider pieces for the same amount of material.

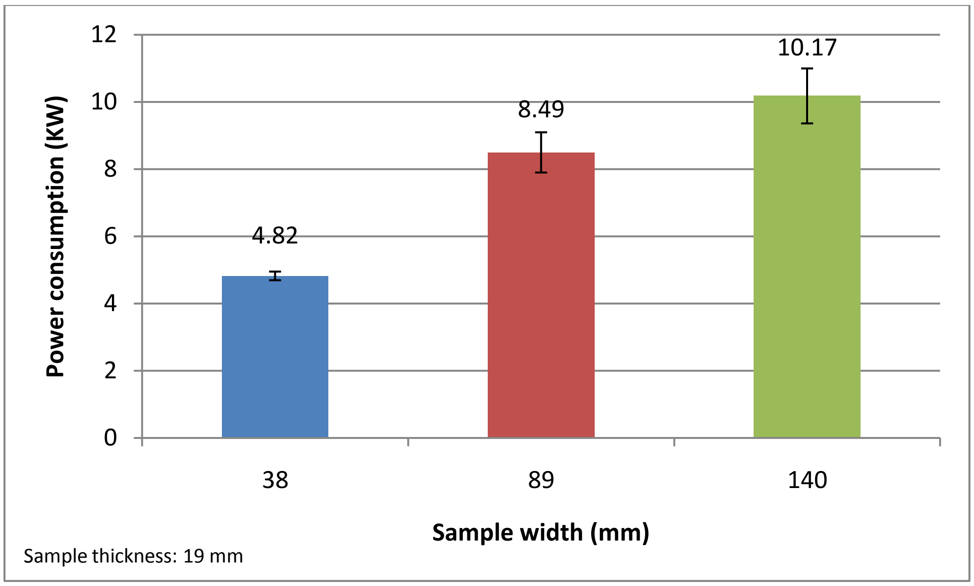

Figure 3-16: Power consumption for shredding of pieces of lumber with different widths (Each error bar is constructed using 1 standard deviation from the sample)

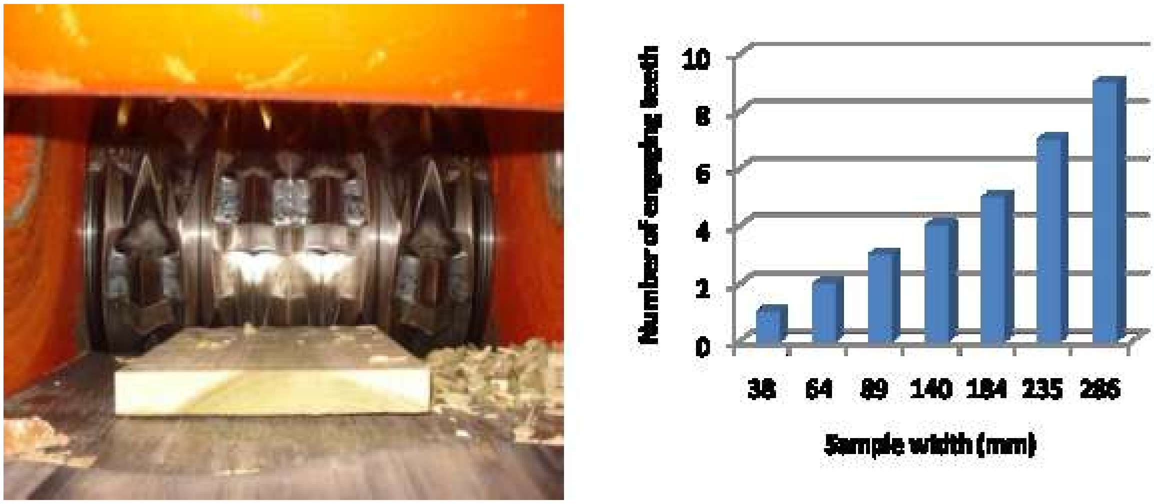

Figure 3-17: Number of engaging teeth for pieces of lumber with different widths

Therefore, based on the previous results, it was decided to use samples with width of 89 mm (4 in nominal) for the final experimentation.

3.2.2.3. Lumber thickness

Three different lumber thicknesses were tested in this series of experiments: 19 mm (1 in nominal), 25.4 mm (1 ¼ in nominal), and 38 mm (2 in nominal). Samples length and width were 89 mm (4 in nominal) and 1.2 m (48 inches). Samples were made out of kiln dried eastern white pine (*Pinus strobus*).

Results obtained from this experiment are presented on Figure 3-18. It was clear that energy consumption for shredding of 19 mm thick samples and 25.4 mm thick samples were very similar. However, energy requirements for shredding of 38 mm thick sample were somewhat higher than those of 19 mm and 25.4 mm thick samples. The previous statements were supported by two statistical tests for means comparison (Tukey-Kramer HSD test and non-parametric Kruskal-Wallis test). Both tests were performed using JMP® version 8 from

SAS®. Details about the statistical tests are shown on Table A 3 shown in the appendices. The difference in energy requirement for shredding of 38 mm thick samples and the rest of samples (19 mm and 25.4 mm samples) may be ascribed to the higher power consumption required for shredding of the former samples. In fact, electrical power required to process 38 mm thick samples reached a maximum value of roughly 21 kW (28 HP). On the other hand, maximum power required for shredding of 19 mm and 25.4 mm thick samples were around 9 kW (12 HP) and 14 kW (19 HP), respectively. Therefore, based on the results shown by this experiment, final experimentation was carried out using 19 mm (1 in nominal) thick samples.

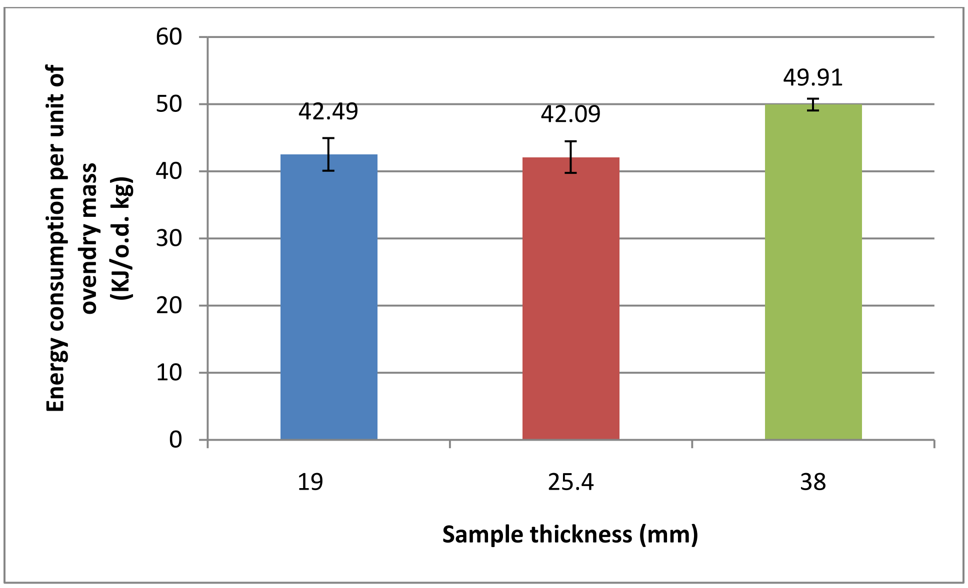

Figure 3-18: Energy consumption for shredding of pieces of lumber with different thicknesses (Each error bar is constructed using 1 standard deviation from the sample)

In conclusion, by combining the results obtained from these series of preliminary experiments, it was decided that final experimentation regarding size reduction of wood on the horizontal shredder would be carried out using 19 mm x 89 mm x 1220 mm (1 in x 4 in x 48 in nominal) lumber pieces.

3.2.3. Size reduction of high moisture content wood chips on the rotary hammermill

This preliminary experimentation was intended to test the hammermill's capacity to process wood chips in green condition (high moisture content). For this reason, wood chips obtained from size reduction of green eastern white pine (*Pinus strobus*) lumber were processed on the rotary hammermill. The initial and desired final sizes of chips were 15 – 20 mm and 3 mm, respectively. Average moisture content of chips processed in this experimentation was 34 percent. Power consumption was the parameter monitored in this experiment.

Figure 3-19 illustrates the power consumption for hammermilling of green chips. It can be observed that power consumption steeply increased until the hammermill shut down due to overload.

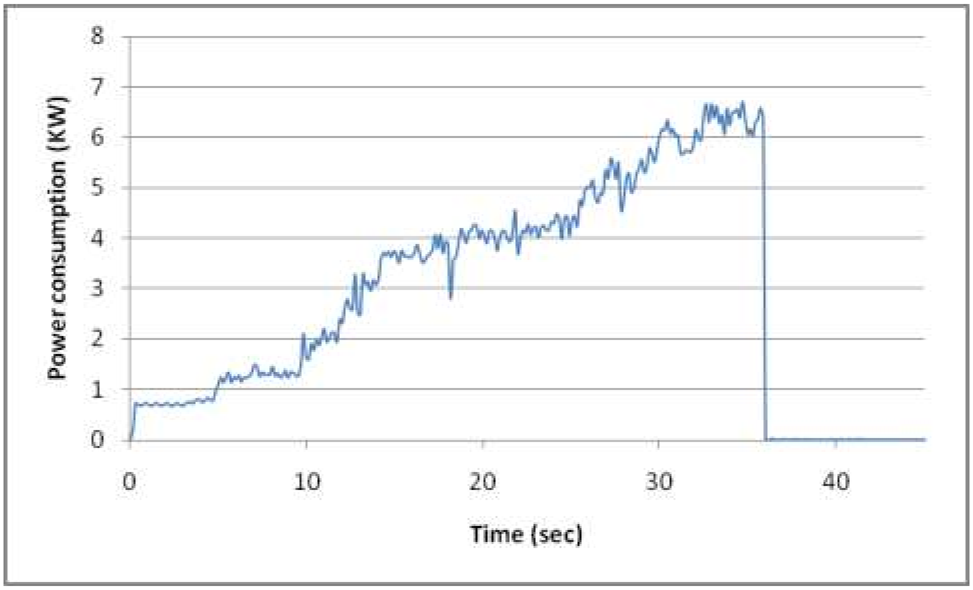

Figure 3-19: Power consumption for size reduction of high moisture content wood chips on the rotary hammermill

The hammermill became overloaded when processing green chips because chips bundled together forming a thick mass of wet chips in the milling chamber which prevented the hammers from spinning (Figure 3-20). These results support those given in the literature (Trass, 1984).

Figure 3-20: High moisture content chips bundled together in the milling chamber of the rotary hammermill

In conclusion, due to the inability of the hammermill to handle wood chips in green condition (high moisture content), it was decided that for final experimentation only dry material (moisture content ≤ 12%) would be processed on the rotary hammermill.

3.2.4. Densification of high moisture content chips

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, raw material properties, etc. In the case of wood, moisture content usually ranges from 8 to 12 percent, which is suitable for wood densification (Karlhager, 2008). Nonetheless, the objective of this preliminary experimentation was to evaluate the possibility of compacting wood chips with moisture content greater than 12 Percent. This experimentation was carried out using green southern yellow pine chips (*Pinus spp.*) with moisture content between 15 and 20 percent. Chips size was 12 – 15 mm. Particles were compacted using a piston type briquetting press. Briquettes obtained are shown on Figure 3-21.

Figure 3-21: Wood briquettes made out of high moisture content chips

From Figure 3-21, it was clear that densification was very poor to the point that chips could not hold together for long. In fact, briquettes swelled excessively right after coming out of the briquetting press pipeline and eventually disintegrated. These results were in accordance to 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 which disintegrated easily.

Therefore, results obtained in this experiment led to the use of only low moisture content chips (moisture content ≤ 12%) in the final experimentation.

CHAPTER 4

RESULTS AND ANALYSIS

The objective of this chapter is to illustrate the results obtained from the experimentation of this project. This chapter was broken down into several sections for better understanding: energy consumption for size reduction of wood, energy consumption for drying of wood particles, energy consumption for densification of wood chips and particles, calorific values of wood, energy balance for production of briquettes, and energy density of wood briquettes. In addition, analysis and discussion of the results attained in this project are presented in order to offer possible explanations.

4.1. Energy consumption for size reduction of wood

Two different pieces of equipment for wood size reduction were employed in this project: a horizontal shredder and a rotary hammermill. The comminution operation carried out using the horizontal shredder was called primary size reduction while hammermilling was labeled as secondary size reduction. For this reason, this section was broken down into two sub-sections: energy consumption during primary size reduction (shredding) and energy consumption during secondary size reduction (hammermilling).

4.1.1. Energy consumption during primary size reduction (shredding)

This section refers to the energy consumption for size reduction of wood using a horizontal shredder. Three factors which affected energy consumption during shredding were considered: wood species (eastern white pine, southern yellow pine, and yellow poplar), particle size obtained from primary size reduction (12-15 mm and 15-20 mm), and initial condition of the raw material (dry lumber and wet lumber). The response parameter was the net energy for size reduction of wood per unit of ovendry mass.

A statistical analysis was performed in order to analyze which levels of a factor were different from each other and how the levels interacted with other factors. This statistical analysis involved an analysis of variance (ANOVA) at a significance level of $\alpha = .05$. A total of 983 observations were taken into consideration for the statistical analysis. The model for the ANOVA was built using JMP® version 8 from SAS®. Details of the statistical analysis are shown in Table A 4 in the appendices.

The statistical analysis showed that the main effects of the three factors evaluated were significant on the net energy consumption for shredding of wood (Table A 4). In the case of wood species, energy consumption for shredding of yellow poplar was higher than that of softwoods (Figure 4-1). However, there was no significant difference in energy consumption between the softwood species. Higher energy consumption associated with shredding of yellow polar may be attributed to its higher shear strength perpendicular to the grain if 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).

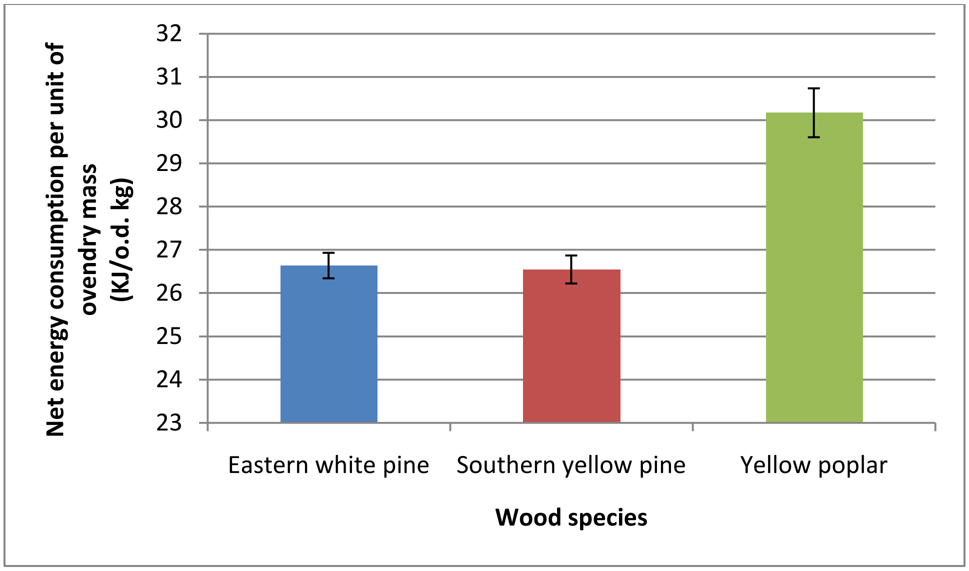

Figure 4-1: Energy consumption during primary size reduction (shredding) sorted by wood species (Each error bar is constructed using 1 standard error from the mean)

On the other hand, it was interesting the similarity in energy consumption for shredding of eastern white pine and southern yellow pine because their physical (specific gravity) and mechanical properties differ (Forest Products Laboratory, 1999). In fact, eastern white pine (*Pinus strobus*) is classified as a "soft pine" species while southern yellow pine (*Pinus spp.*) belongs to the so-called "hard pines" (Hoadley, 1990). Moreover, based on its mechanical properties, southern yellow pine may be considered more difficult to process than both eastern white pine and yellow poplar (Forest Products Laboratory, 1999). A possible explanation for such behavior may be found in the two parameters used to determine the energy consumption for size reduction: power consumption and processing period. Power consumption for shredding of southern yellow pine was the highest among the wood species considered in this experimentation (Figure 4-2). Conversely, processing period related to southern yellow was the shortest among the wood species studied in this project (Figure 4-3). Thus, it seemed that due to its the mechanical properties , shredding of southern yellow pine demanded higher electrical power which caused the shortening of the processing period during size reduction – the shredder was able to process more material per unit of time at a higher electrical demand rate. As a result, energy consumption for shredding of southern yellow pine ended up being similar to that of eastern white pine (Figure 4-1). Therefore, the mutual variation of the parameters (power consumption and processing period) used to determine energy requirements for shredding seemed to have an important bearing in the energy consumption for primary size reduction (shredding) of wood. Furthermore, although it was not studied in this project, it may be speculated that the fracture mechanisms associated to each wood species might also affects the energy requirements for size reduction.

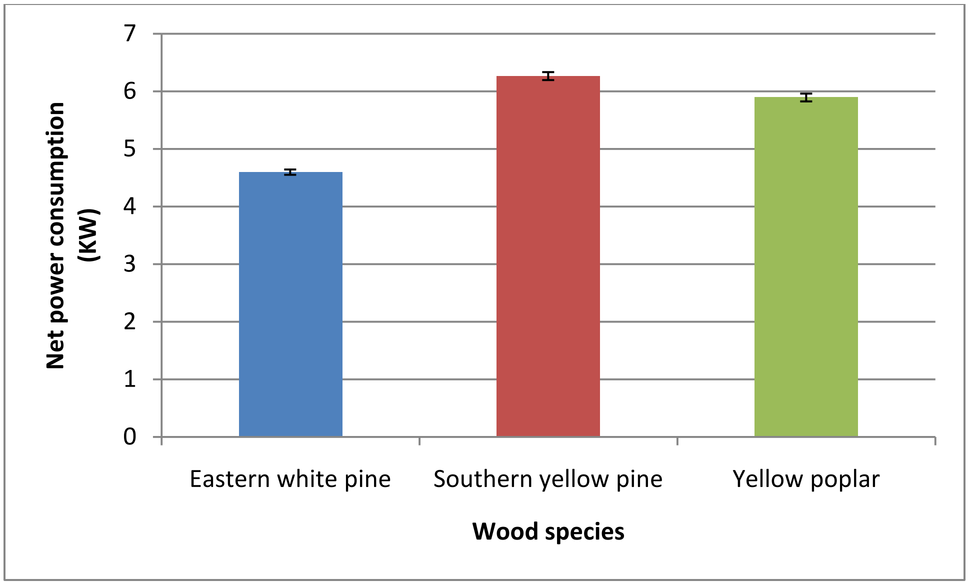

Figure 4-2: Power consumption during primary size reduction (shredding) sorted by wood species (Each error bar is constructed using 1 standard error from the mean)

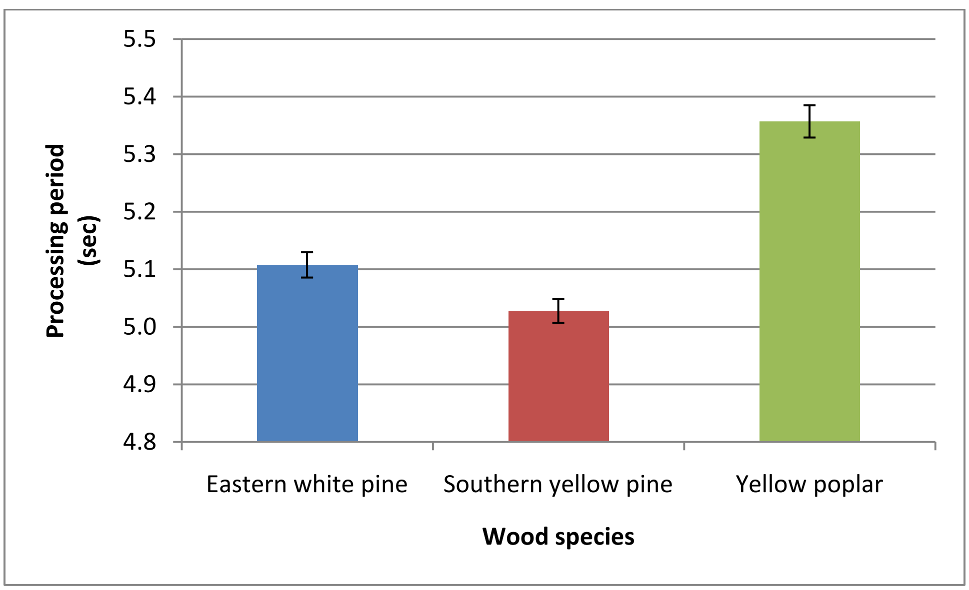

Figure 4-3: Processing period during primary size reduction (shredding) sorted by wood species (Each error bar is constructed using 1 standard error from the mean)

Figure 4-4 illustrates the energy consumption for shredding of wood depending on the particle size target (12-15 mm or 15-20 mm). It seemed that energy consumption for size reduction and the final particle size obtained from a size reduction operation were inversely proportional. Hakkila (1989), Jones (1981), Cadoche et al. (1989) and Holtzapple at el. (1989) reported similar conclusions.

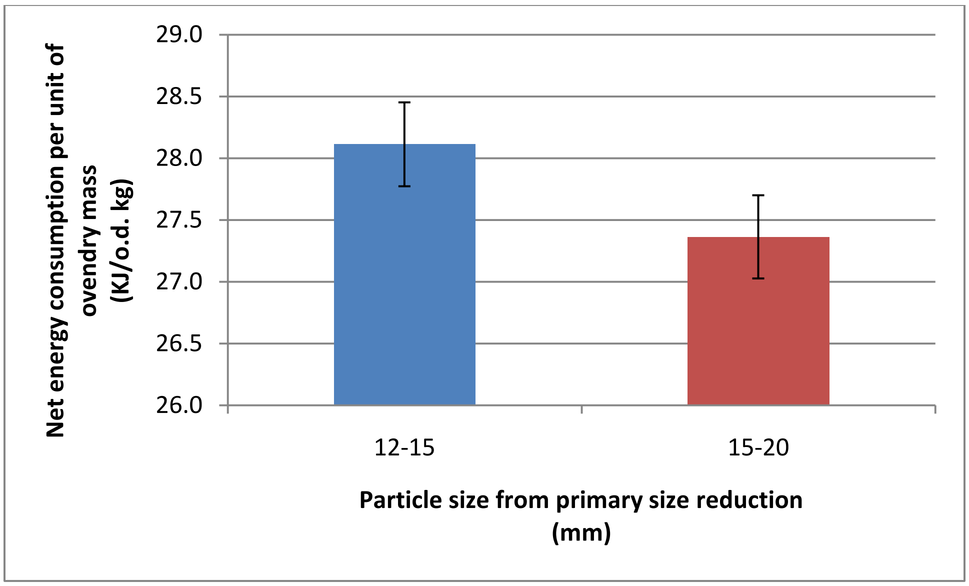

Figure 4-4: Energy consumption during primary size reduction (shredding) sorted by particle size obtained from primary size reduction (Each error bar is constructed using 1 standard error from the mean)

With regard to the initial condition of the raw material, it was observed that shredding of dry lumber required more electrical energy than shredding of wet lumber (Figure 4-5). The explanation for these results may be ascribed to 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 percent moisture content) was more difficult to process than wet (green) wood (Forest Products Laboratory, 1999).

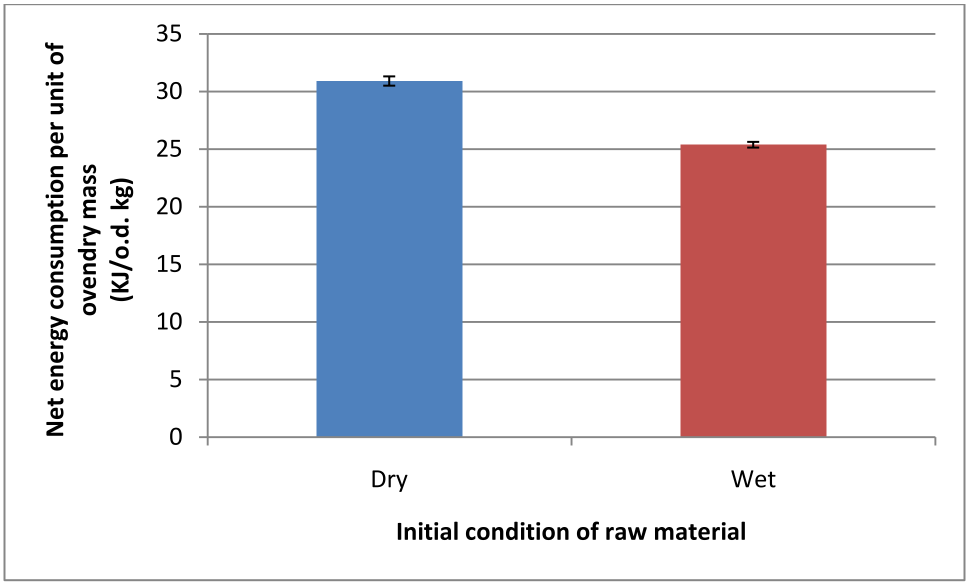

Figure 4-5: Energy consumption during primary size reduction (shredding) sorted by initial condition of the raw material (Each error bar is constructed using 1 standard error from the mean)

The statistical analysis also showed that some interactions between the factors considered were significant with respect to the energy consumption for wood shredding (Table A 4). For example, in the case of eastern white pine, energy consumption during primary size reduction was higher when the particle size obtained after size reduction was 12-15 mm chips than when the material obtained was 15-20 mm chips (Figure 4-6). This trend was in accordance with what has been reported in the literature (Hakkila, 1989); (Cadoche & López, 1989); (Holtzapple et al., 1989). On the other hand, energy consumption for primary size reduction of yellow poplar and southern yellow pine lumber into either 12-15 mm or 15-20 mm chips was not statistically different within each species (Table A 4).

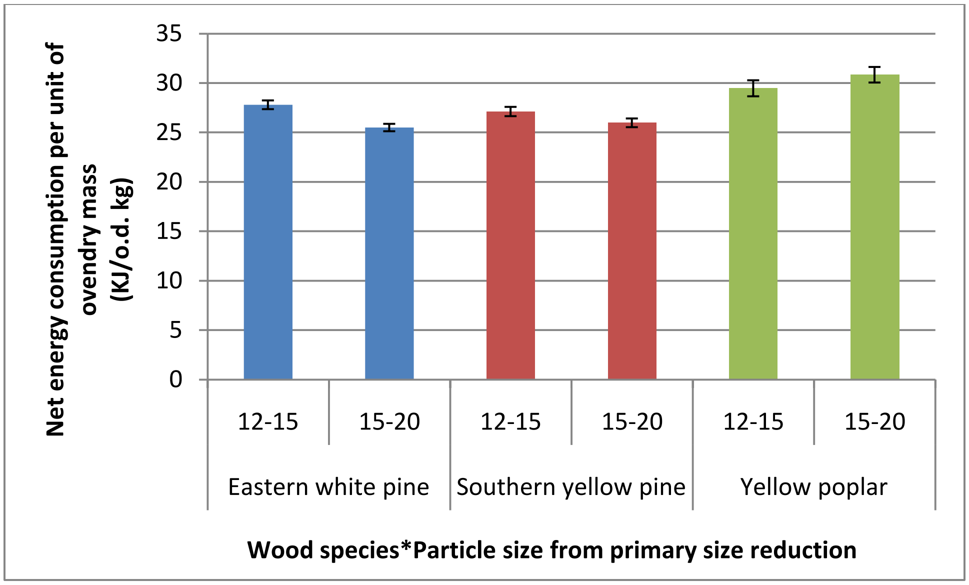

Figure 4-6: Energy consumption during primary size reduction (shredding) sorted by wood species and particle size obtained from primary size reduction (Each error bar is constructed using 1 standard error from the mean)

The interaction between wood species and the initial condition of the raw material were also found to be significant with regard to the energy requirements for wood shredding (Table A 4). In the case of eastern white pine, shredding of kiln-dried lumber required slightly higher energy than shredding of wet lumber (Figure 4-7). However, energy consumption for size reduction of kiln-dried southern yellow pine lumber was lower than that associated with shredding of wet southern yellow pine lumber (Figure 4-7). On the other hand, observations of energy consumption for shredding of kiln-dried and wet yellow poplar lumber were similar to that of eastern white pine lumber but much more pronounced (Figure 4-7). These results might be explained based on Koch's observations (1964) who reported that increased moisture content may cause certain species (e.g. Douglas fir and sugar pine) to have larger friction coefficients compared to dry values while the reverse may be true for the case of other species (e.g. birch and white ash). Thus, according to Koch (1964), the interaction between wood species and moisture content seemed to have an important bearing on the power consumption of machining operations.

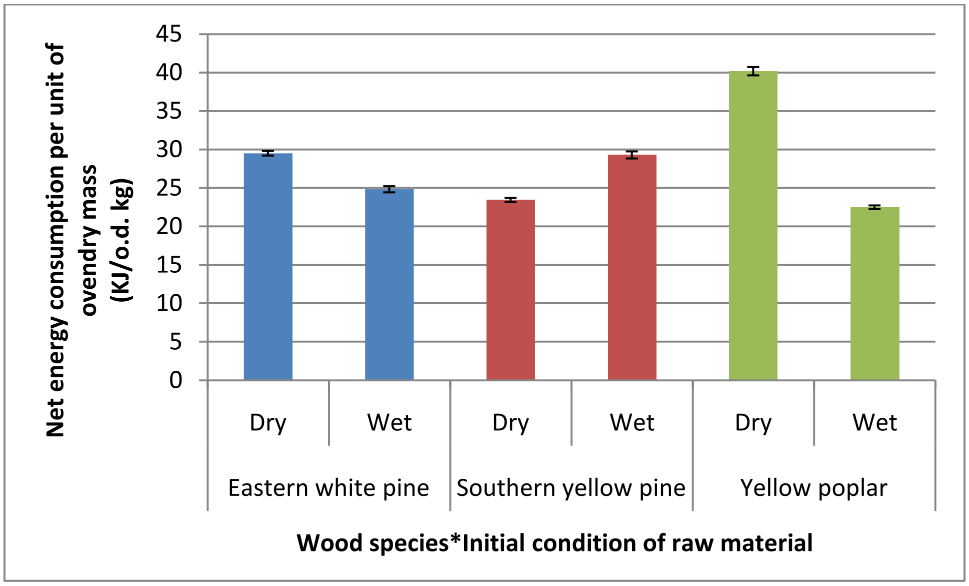

Figure 4-7: Energy consumption during primary size reduction (shredding) sorted by wood species and initial condition of the raw material (Each error bar is constructed using 1 standard error from the mean)

The three-way interaction among the factors considered in this section turned out significant with respect to the energy required for wood shredding (Table A 4). As can be observed in Figure 4-8, the analysis of this three-way interaction allowed identifying the maximum and minimum energy requirements for primary size reduction of wood for each treatment considered in this project. For example, the highest energy consumption for shredding of wood was obtained when dry yellow poplar lumber was processed to obtain 15-

20 mm chips. On the contrary, the lowest energy consumption was attained when wet yellow poplar lumber was shred to obtain 12-15 mm wood chips.

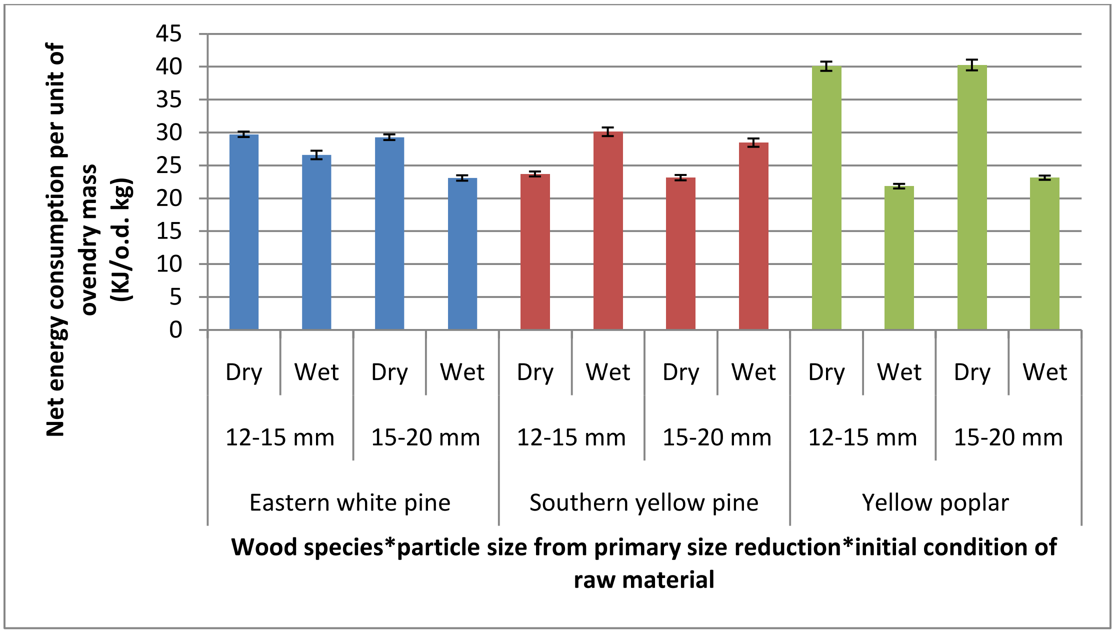

Figure 4-8: Energy consumption during primary size reduction (shredding) sorted by wood species, particle size obtained from primary size reduction, and initial condition of the raw material (Each error bar is constructed using 1 standard error from the mean)

4.1.2. <u>Energy consumption during secondary size reduction (hammermilling)</u>

This section is focused on the energy requirements for hammermilling of dried wood chips using the rotary hammermill (secondary size reduction). Factors taken into consideration in this experimentation were: wood species (eastern white, pine southern yellow pine, and poplar), chips size (12-15 mm and 15-20 mm), and initial condition of the raw material before primary size reduction (dry lumber and wet lumber). The response parameter analyzed was the net energy consumption for size reduction of wood chips per unit of ovendry mass.

A statistical analysis was performed in order to analyze which levels of a factor were different from each other and how the levels interact with other factors. This statistical analysis involved included an analysis of variance (ANOVA) at a significance level of α = 0.05. A total of 103 observations were considered to build the ANOVA model. The model for the ANOVA was built using JMP® version 8 from SAS®. Details of the statistical analysis are shown on Table A 5 shown in the appendices.

From the statistical analysis (Table A 5), it could be observed that the main effects of the three considered factors were significant with regard to the energy consumption for hammermilling of wood chips. In the case of wood species, hammermilling of southern yellow pine chips consumed the highest amount of energy among all the species (Figure 4-9). On the other hand, energy requirements for size reduction of eastern white pine and yellow polar chips were very similar (Figure 4-9).

Figure 4-9: Energy consumption during secondary size reduction (hammermilling) sorted by wood species (Each error bar is constructed using 1 standard error from the mean)

These results may be explained based on the several failure mechanisms underwent 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 with respect to eastern white pine and yellow poplar (Forest Products Laboratory, 1999), energy requirements for hammermilling of southern yellow pine were higher than those for hammermilling of the other two species. In contrast, compressive strength, shear strength parallel to the grain, impact bending strength, modulus of elasticity and rupture, and hardness of eastern yellow pine and yellow poplar may be comparable – although values for yellow poplar were somewhat higher. For this reason, the energy consumption values for processing of eastern white pine and yellow poplar were similar.

The size of the chips processed on the rotary hammermill showed to be also significant with respect to the energy requirements for hammermilling (Table A 5). Figure 4-10 illustrates that hammermilling of 12-15 mm wood chips required less energy than hammermilling of 15-20 mm wood chips. It is important to remember that all wood chips – regardless their initial size – were reduced to a final particle size of 3 mm in the hammermill. Therefore, it should not be surprising that energy consumption for size reduction of larger chips (15-20 mm) was higher than that of smaller chips (12-15 mm).

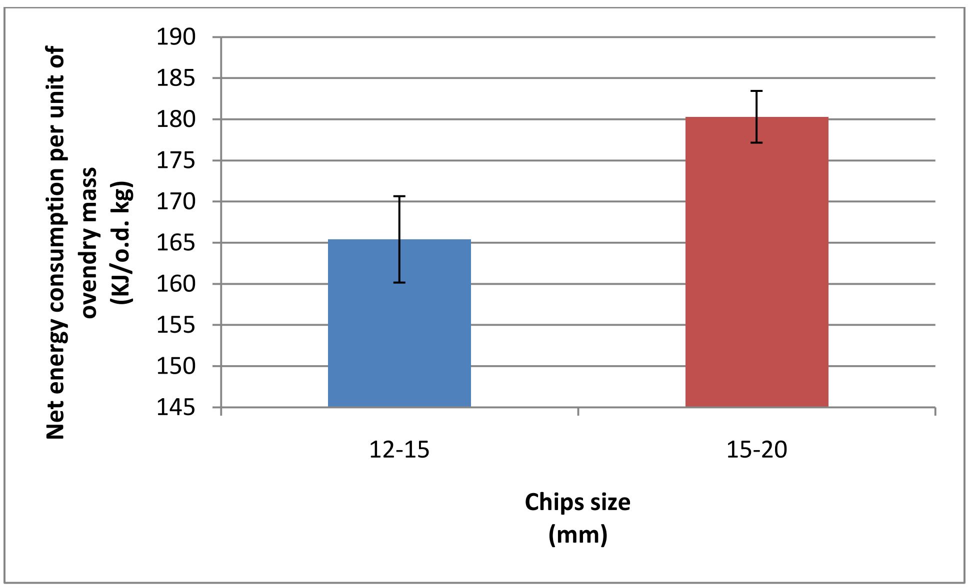

Figure 4-10: Energy consumption during secondary size reduction (hammermilling) sorted by chips size (Each error bar is constructed using 1 standard error from the mean)

Even though wet wood chips were air dried before hammermilling, the initial condition of the wood (wet or dry) prior to primary size reduction (shredding) had an influence on the energy requirements during hammermilling (Table A 5). From Figure 4-11, it can be observed that processing of wood chips that were initially wet required more energy than hammermilling of 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. For instance, it seemed that compressive and shear strength of wood chips obtained after primary size reduction were affected by the initial condition of the material (wet or dry lumber) to such extent that chips obtained from wet lumber might be more resistant to compressive and shear stresses than chips obtained from dry wood. Furthermore, it might be speculated that for a specific range of chips size (e.g. 15-20 mm) the average particle size could have been larger for wet wood than for dry wood. Therefore, higher energy requirements associated with processing of chips obtained from wet lumber might be a consequence of the initial condition (low or high moisture content) during primary size reduction (shredding).

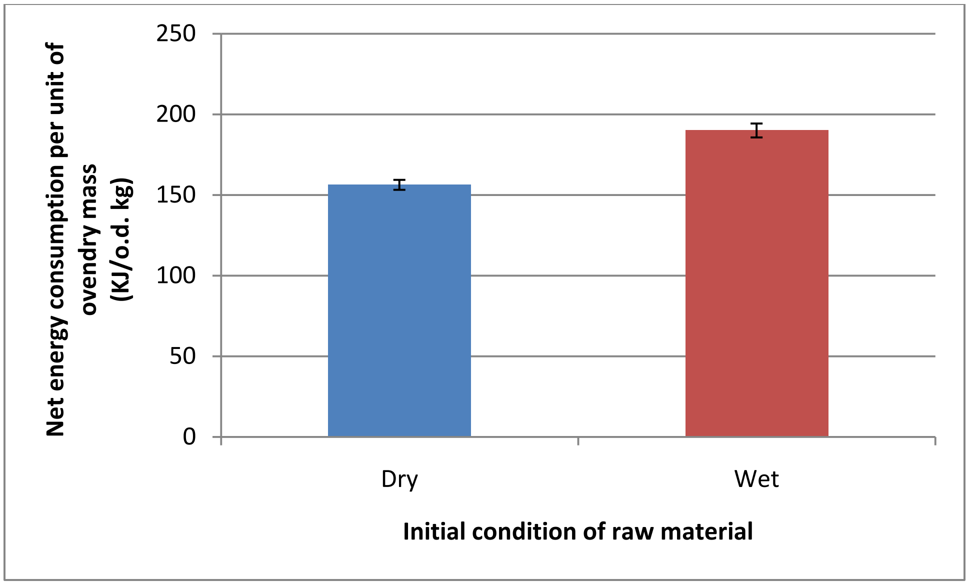

Figure 4-11: Energy consumption during secondary size reduction (hammermilling) sorted by initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

Similar to primary size reduction, a couple of interactions among the factors considered in this experimentation turned out to be significant with respect to the energy requirements for hammermilling of wood chips (Table A 5). In the case of yellow poplar chips, energy requirements were higher for hammermilling of 15-20 mm chips than for hammerilling of 12-15 mm chips (Figure 4-12). On the other hand, there was no significant difference in energy consumption between hammermilling of 12-15 mm and 15-20 mm eastern white pine chips (Table A 5). This was also true for 12-15 mm and 15-20 mm southern yellow pine chips (Table A 5).

Figure 4-12: Energy consumption during secondary size reduction (hammermilling) sorted by wood species and chips size (Each error bar is constructed using 1 standard error from the mean)

The interaction between wood species and the initial condition of wood before primary size reduction was also significant with respect to the energy requirements for secondary size reduction of wood chips (Table A 5). In the case of eastern yellow pine and yellow poplar chips, energy consumption during secondary size reduction was higher when chips were obtained from wet lumber than when chips were obtained from dry lumber (Figure 4-13). On the other hand, there was no significant difference in energy requirement for hammermilling of southern yellow pine chips obtained from either wet or dry lumber (Table A 5).

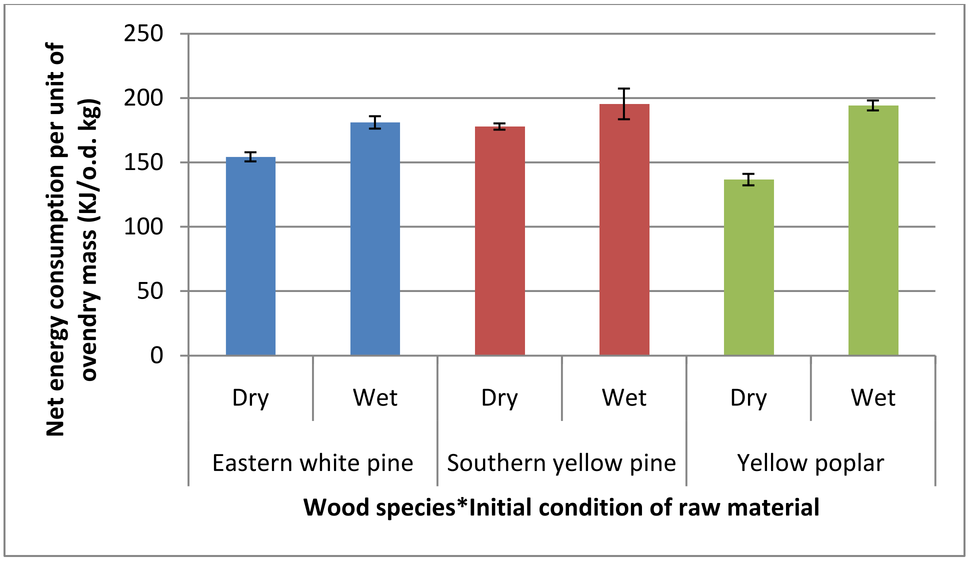

Figure 4-13: Energy consumption during secondary size reduction (hammermilling) sorted by wood species and initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

The highest energy consumption for hammermilling of wood chips was attained when 15-20 mm wet yellow polar chips were processed (205.7 KJ/o.d. kg). On the contrary, the lowest energy consumption was associated to hammermilling of 12-15 mm dry yellow poplar chips (119 KJ/o.d. kg).

4.2. Energy consumption for drying of wood chips

Raw material with high moisture content must be conditioned prior to densification in order to avoid formation of steam during compaction that may result in explosion (Bhattacharya, 1989). Moreover, densified products obtained out of high moisture content raw material tend to disintegrate easily (Li & Liu, 2000). For this reason, high moisture content wood chips and particles used in this project were subjected to a process of air-drying in order to reduce their moisture content.

Thermal energy associated with the process of air drying was determined using Equation 2.11. Results are presented in Table 4-1. The thermal energy required to evaporate one kg of water was nearly 3 MJ/kg H_2O – regardless of the wood species. Such 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/ovendry kg) for drying of eastern white pine and yellow poplar chips was roughly twice as high as that of southern yellow pine chips. Such difference in the energy use was attributed to the higher initial moisture content of eastern white pine and yellow poplar with respect to southern yellow pine –the more water is in wood, the more energy is required for drying.

Table 4-1: Thermal energy required for air drying of wood chips

Wood species	Initial MC (%)	Final MC (%)	Amount of water evaporated (kg H_2O / o.d. kg)	Energy requirements	
				MJ / kg H_2O	MJ / o.d. kg
Eastern white pine (*Pinus strobus*)	50.9	5.7	0.453	2.96	1.34
Southern yellow pine (*Pinus spp.*)	27.6	5.9	0.217	2.94	0.638
Yellow poplar (*Liriodendron tulipifera*)	45.9	5.3	0.405	2.98	1.21

MC: moisture content
o.d. : oven-dry

4.3. Energy consumption for densification of wood chips and particles

This section refers to the energy requirements for compaction of wood chips and particles into briquettes. As mention before, densification of wood chips and particles were performed on a piston type briquetting press. Three factors were evaluated: wood species (eastern white pine, southern yellow pine, and yellow poplar), initial condition of the raw material (wet or dry lumber) prior to primary size reduction (shredding), and particle size of the material intended to compact. The response parameter analyzed was the net energy consumption for densification of wood chips and particles per unit of ovendry mass.

A statistical analysis was performed in order to analyze which levels of a factor were different from each other and how the levels interacted with other factors. This statistical analysis involved an analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$. Fifty two observations were considered to build a model for ANOVA under JMP® version 8 from SAS®. Details of the statistical analysis are shown on Table A 6 in the appendices.

Based on the statistical analysis (Table A 6), the main effects of the three factors considered were significant with respect to the energy required for densification of wood chips and particles. For instance, the energy consumption for densification of yellow poplar chips and particles was higher than that for compaction of southern yellow pine chips and particles (Figure 4-14). However, energy requirements for compaction of yellow poplar chips and particles resulted to be similar to those of eastern white pine. It is interesting that 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.

Figure 4-14: Energy consumption for densification of wood chips and particles sorted by wood species (Each error bar is constructed using 1 standard error from the mean)

The initial condition of the raw material before primary size reduction (shredding) also resulted in a significant effect on the energy required for densification of wood chips and particles (Table A 6). It can be observed that it required more energy to compact chips and particles obtained from wet wood (Figure 4-15). As mentioned above, 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. As a result, it required more energy to compact (compress) material obtained from wet wood than chips obtained from dry lumber.

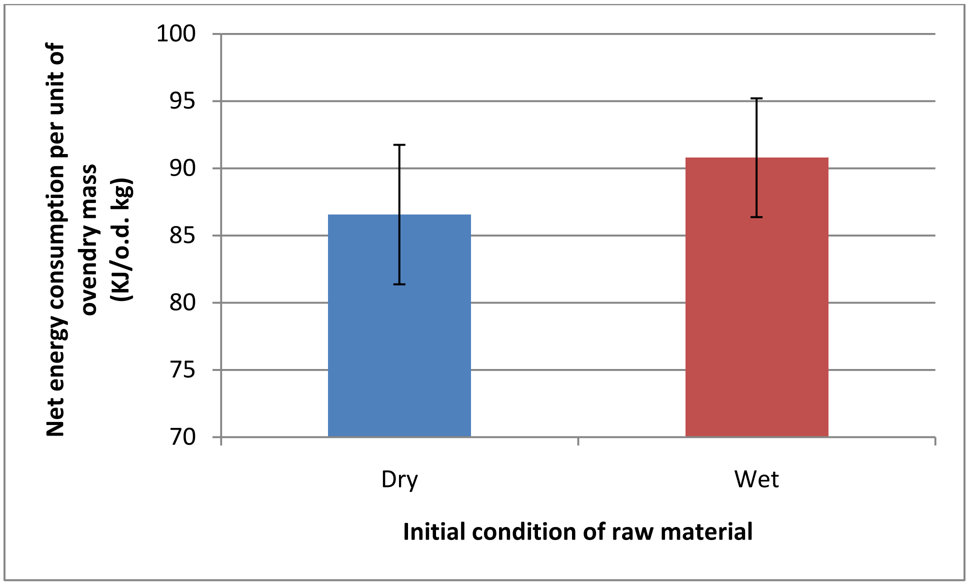

Figure 4-15: Energy consumption for densification of wood chips and particles sorted by initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

Energy consumption for densification of wood chips and particles was also significantly affected by the size of the material intended to compact (Table A 6). Figure 4-16 illustrates that energy requirements for densification of 3 mm wood particles were lower than those associated with 12-15 mm wood chips. Based on these results, it seemed that it required less energy to compress and compact wood particles (3 mm) than relatively large wood chips (12-15 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 was 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).

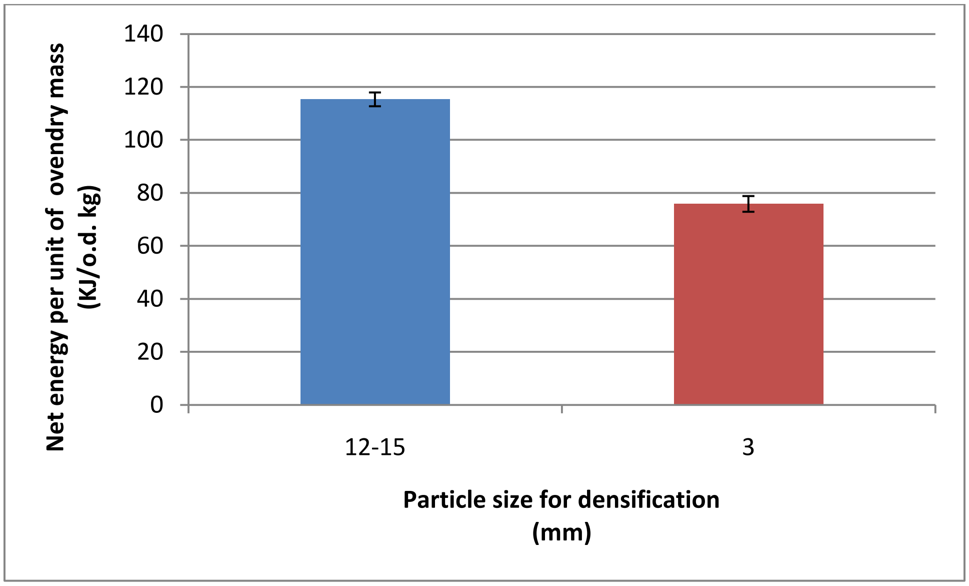

Figure 4-16: Energy consumption for densification of wood chips and particles sorted by particle size of the material intended for densification (Each error bar is constructed using 1 standard error from the mean)

As mentioned above, the interaction among the factors considered in this experimentation had an important bearing on the energy consumption for densification of wood chips and particles (Table A 6). For example, in the case of southern yellow pine chips and particles, energy requirements for densification were higher when the initial condition of the material before primary size reduction (shredding) was wet than when the material was initially dry (Figure 4-17). However, energy consumption for compacting of eastern white pine chips and particles was not significantly different whether the initial condition of the material before shredding was dry or wet (Table A 6). This was also true for yellow poplar chips and particles (Table A 6).

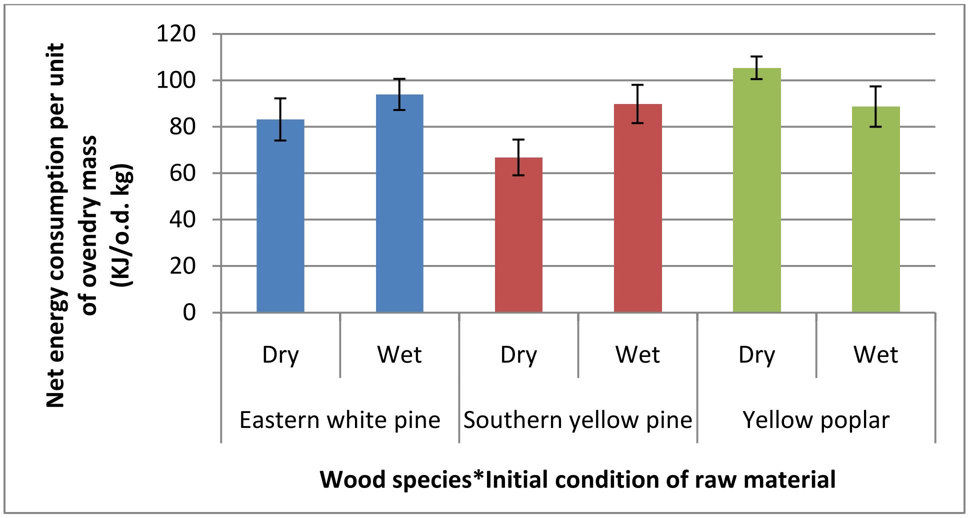

Figure 4-17: Energy consumption for densification of wood chips and particles sorted by wood species and initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

The interaction between wood species and particle size of the material intended to compact was also significant with regard to the energy consumption for densification (Table A 6). In fact, energy requirements for compaction of 3 mm particles were lower than for compaction of 12-15 mm chips, regardless of the wood species (Figure 4-18). Once again, lower energy requirements for compaction of 3 mm wood particles were due to higher Van de Walls forces, better ability to fill voids, and easier transportation through the feeding auger and the compactions chamber of small wood particles (3 mm) with respect to larger wood chips (12-15 mm)

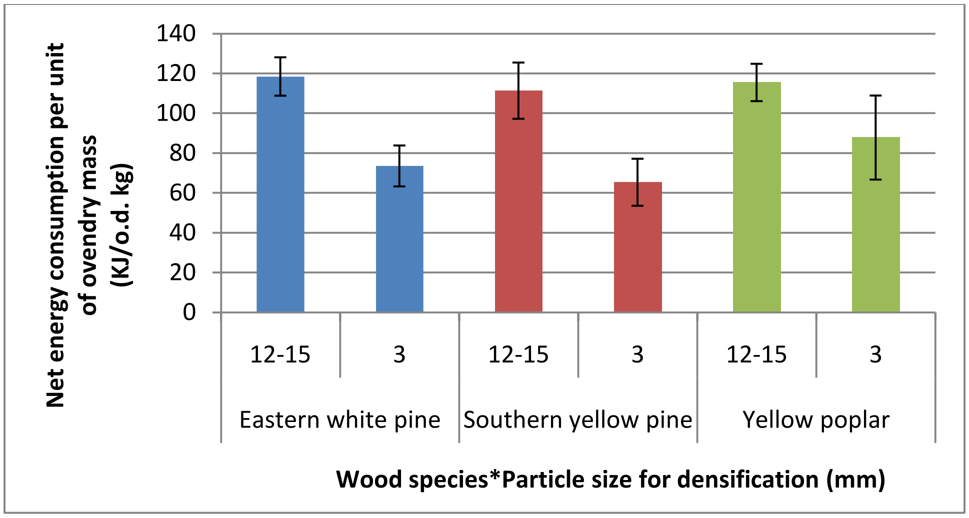

Figure 4-18: Energy consumption for densification of wood chips and particles sorted by wood species and particle size of the material intended for densification (Each error bar is constructed using 1 standard error from the mean)

Similarly, the interaction between the initial condition of the raw material prior to size reduction and the particle size of the material intended to compact resulted to be significant with respect to the energy consumption for compaction of woody material (Table A 6). For instance, in the case of material that was obtained from dry lumber, energy consumption for densification was higher for 12-15 mm chips than for 3 mm particles (Figure 4-19). The same was also true for material obtained from wet wood (Figure 4-19). It is important to remark that there was no difference in energy requirements for compaction of 3 mm particles regardless of the origins of the material (wet or dry).

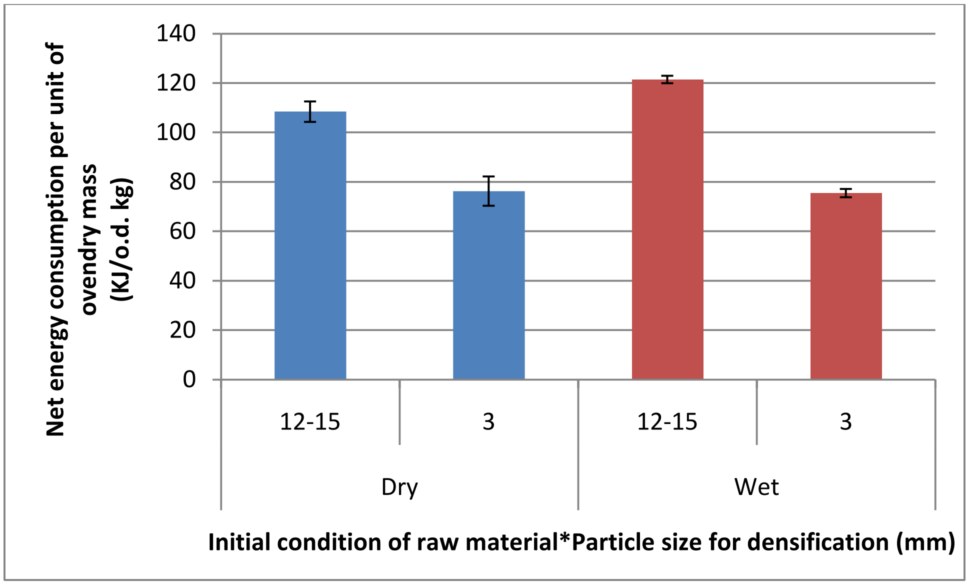

Figure 4-19: Energy consumption for densification of wood chips and particles sorted by initial condition of the raw material before primary size reduction and particle size of the material intended for densification (Each error bar is constructed using 1 standard error from the mean)

Finally, the three-way interaction among the factors evaluated was also significant with respect to the energy consumption for densification of wood chips and particles (Table A 6). This interaction was especially useful to point out maximum and minimum energy consumption for densification under the experimentation set up. Results showed that the minimum energy requirements for densification were observed when compacting 3 mm southern yellow pine particles obtained from initially wet lumber (Figure 4-20). Conversely, the maximum energy consumption was generated when compressing 12-15 wood chips obtained from initially green yellow poplar lumber (Figure 4-20).

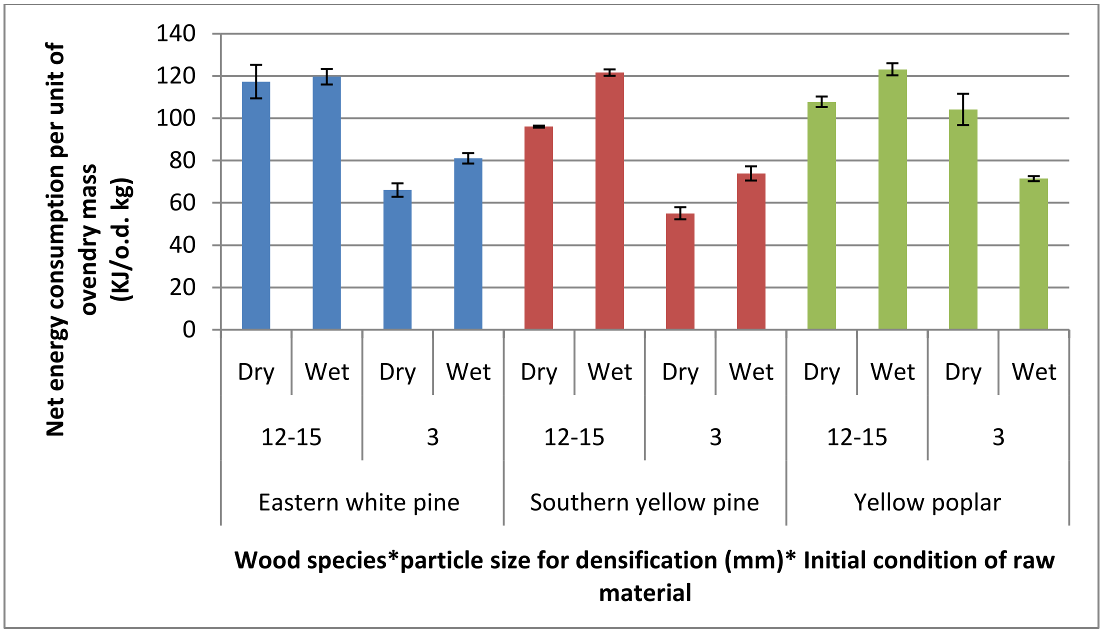

Figure 4-20: Energy consumption for densification of wood chips and particles sorted by wood species, particle size of the material intended for densification, and initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

4.4. Calorific values of wood species

Gross and net calorific values of the wood species considered in this project were determined in order to compute the amount of energy that can be obtained from combustion of wood briquettes. It is important to remind that the gross calorific value was the amount of energy available (heat) produced by complete combustion of a unit quantity of solid fuel under specified conditions such that all water in the products remains in liquid form. On the other hand, the net calorific value was equivalent to the energy (heat) produced by combustion of a unit quantity of solid fuel under the assumption that all water in the products remains in the form of vapor. Results from both gross and net calorific values of wood are summarized on Table 4-2.

Table 4-2: Gross and net calorific values of wood species

Wood species	Gross calorific value (MJ / ovendry kg)		Net calorific value (MJ / kg)	
	Mean	Standard deviation	Mean	Standard deviation
Eastern white pine (*Pinus strobus*)	21.09	0.1696	18.78	0.1919
Southern yellow pine (*Pinus spp.*)	19.73	0.0492	17.57	0.0632
Yellow poplar (*Liriodendron tulipifera*)	18.98	0.2205	17.04	0.2755
Sample size per species: 6				

It can be observed on Table 4-2 that both gross and net calorific values of softwood species were higher than those of the hardwood species considered in this project. Such values were in accordance with those given in the literature (Bowyer, Shmulsky, & Haygreen, 2007); (White, 1987): (Harris, 1984). Higher calorific values associated with softwood species may be attributed to the resin content in such specie. In fact, the calorific value of resin in wood is roughly twice as high as that of wood (Bowyer et al., 2007). Therefore, resinous species have higher calorific content than those without resin.

4.5. Energy balance for production of wood briquettes

It has been mentioned before that wood densification is an energy intensive process. In fact, size reduction, drying, and densification were the highest energy consuming operations for production of densified products (Świgoń & Longauer, 2005). Therefore, the objective of this section was to compare the energy requirements for production of wood briquettes (input energy) with the amount of energy that could be obtained out of wood briquettes through combustion (output energy).

The energy requirements for production of wood briquettes (input energy) were associated to the energy required to carry out the basic operations for manufacturing of wood briquettes: size reduction, drying, and densification. On the other hand, the energy that can 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:

$$E_{shredding} + E_{hammermilling} + E_{drying} + E_{densification} = E_{briquettes} \qquad \text{(Eq. 4.1)}$$

where:

$E_{shredding}$: energy requirements for shredding of lumber

$E_{hammermilling}$: energy requirements for hammermilling of wood chips

E_{drying}: energy requirements for drying of wood chips

$E_{densification}$: energy requirements for densification of wood chips and particle

$E_{briquettes}$: net calorific value of wood

Based on the experimentation set-up, there were four possible paths for densification of woody material:

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

In addition, several parameters linked to the raw material were also analyzed: wood species, initial condition of the raw material, particle size of the material obtained from primary size reduction, and particle size intended for densification. The energy requirements for each of these densification alternatives were determined in order to identify maximum and minimum values and compared those values with the energy that can be obtained through combustion of the densified products

Analysis of the energy requirements of each of these densification alternatives showed that the maximum energy expenditure (input energy) was obtained when manufacturing of briquettes through the fourth densification path (Figure 4-21). Specifically, the conversion of wet eastern white pine lumber into briquettes through a manufacturing process that included primary size reduction (shredding) of lumber into 15-20 mm wood chips, drying of wood chips, secondary size reduction (hammermilling) of such wood chips into 3 mm wood particles, and finally compaction of such wood particles into briquettes required almost 1630 KJ/o.d. kg. This amount of energy accounted for around 8.3 percent of the energy in eastern white pine (19.65 MJ/o.d. kg). This proportion was in accordance with that reported by Reed et al. (1978) for a densification process considering similar manufacturing operations. On the other hand, minimum energy consumption (input energy) for densification of woody material was linked to the first densification alternative (Figure 4-21). Particularly, the conversion of dry southern yellow pine lumber into 12-15 wood chips through a single size reduction (shredding) and the subsequently compaction of such chips into briquettes demanded roughly 120 KJ/o.d. kg. This amount of energy was about 0.65 percent of the energy in southern yellow pine (18.33 MJ/o.d. kg).

Minimum and maximum energy requirements for manufacturing of wood briquettes were associated to densification alternatives 1 and 4, respectively. Maximum energy consumption associated to alternative 4 was attributed to the number of manufacturing operations included in this densification path: double size reduction, drying, and compaction. On the other hand, the shorter number of manufacturing operations involved in the first densification alternative (shredding and compaction) lead to the minimum energy consumption for production of wood briquettes.

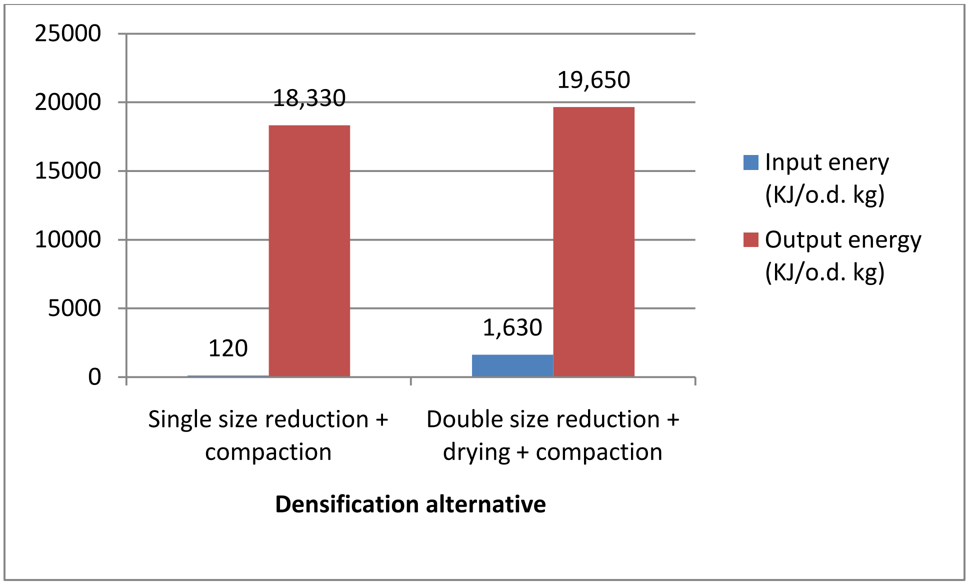

Figure 4-21: Maximum and minimum energy expenditures for manufacturing of wood briquettes

Besides the effect of the number of manufacturing operations for production of wood briquettes, it is also important to note the influence of the drying expenditure on the overall energy consumption of the process. In fact, energy expenditure due to drying of wood chips accounted to roughly 82 percent of the total energy consumption for production of wood briquettes under alternative 4. This value was in accordance with what was reported by EUBIA (2007). This fact can be clearly observed on Figure 4-22 which illustrates the energy requirements average per manufacturing operation for each densification alternative.

The energy requirements average for shredding of lumber were almost 28 KJ/o.d. kg (±7.5 KJ/o.d. kg).This number represented 0.15 percent of the energy average in the wood species considered in this project (18.51 MJ/o.d. kg ± 1.05 MJ/o.d. kg). On the other hand, the energy consumption average for hammermilling of wood chips was 173 KJ/o.d. kg

(±31.6 KJ/o.d. kg) which corresponded nearly to 1 percent of the average energy in the wood species evaluated in this project (18.51 MJ/o.d. kg ± 1.05 MJ/o.d. kg).

In general, the energy consumption average for compaction of wood chips and particles was roughly 88 KJ/o.d. kg (± 22.5 KJ/o.d. kg). This value represents roughly 0.5 percent of the energy average in the wood species considered in this project (18.51 MJ/o.d. kg ± 1.05 MJ/o.d. kg). Such proportions were in accordance with the literature (Reed & Bryant, 1978).

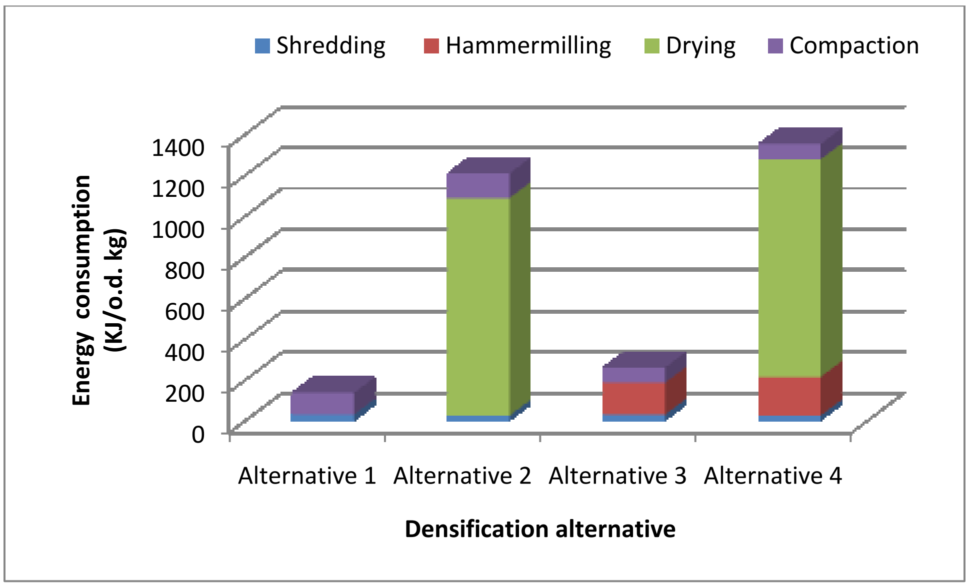

Figure 4-22: Energy requirements average per manufacturing operation for each densification alternative

4.6. Energy density of wood briquettes

This section is focused on the energy density of the briquettes made in the experimentation. The energy density was critical with regards to the storage and transport capacity of densified products. Three factors were evaluated with respect to the energy density of wood briquettes: wood species, initial condition of the raw material prior to shredding, and particle size of the material intended to compact. Energy density of wood briquettes was calculated using Equation 3.6

In order to analyze the effects of the above mentioned factors on the energy density of wood briquettes, a statistical analysis was performed. This statistical analysis involved an analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$ and. A total of 162 observations were taken into consideration for this statistical analysis. The model for ANOVA was built using JMP® version 8 from SAS®. Details of the statistical analysis are shown on Table A-7 displayed in the appendices.

The statistical analysis showed that all the factors considered were significant with respect to the energy density of wood briquettes (Table A 7). For instance, energy density of briquettes varied depending on the wood species. In general, briquettes made out of softwoods had a higher energy density than those briquettes made from the hardwood species (Figure 4-23). Specifically, briquettes made out eastern white pine exhibited the highest energy density among the wood species considered in this project. High energy density values associated to briquettes made from softwoods may be attributed in part to the high calorific values of resinous species.

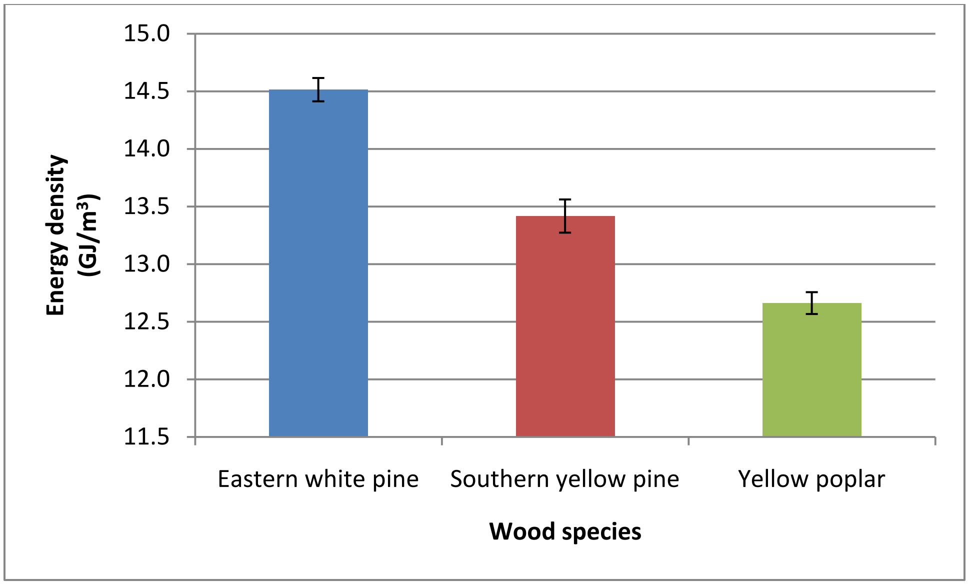

Figure 4-23: Energy density of wood briquettes sorted by initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

The effect of the initial condition of the raw material before primary size reduction on the energy density of the briquettes was also to be significant (Table A 7). Based on the results obtained through the experimentation, wood briquettes made out raw material that was initially wet (moisture content above fiber saturation point) had higher energy densities than those made from raw material that had moisture content below 10 percent (Figure 4-24). It is important to point out that the moisture content of both wood chips and particles was about 6 percent. It has been previously mentioned that the initial condition of the raw material (dry or wet lumber) prior to primary size reduction (shredding) seemed to influence the properties, shapes, and internal structure of the material obtained from shredding. Based on these results, it might be possible that the internal structure of the chips obtained from primary size reduction was affected in such a way that chips and particles obtained from wet lumber might be somewhat denser than chips and particles obtained from dry wood. Consequently, energy density of briquettes made out of material that was initially wet was higher than energy density of briquettes made from chips and particles obtained from dry lumber

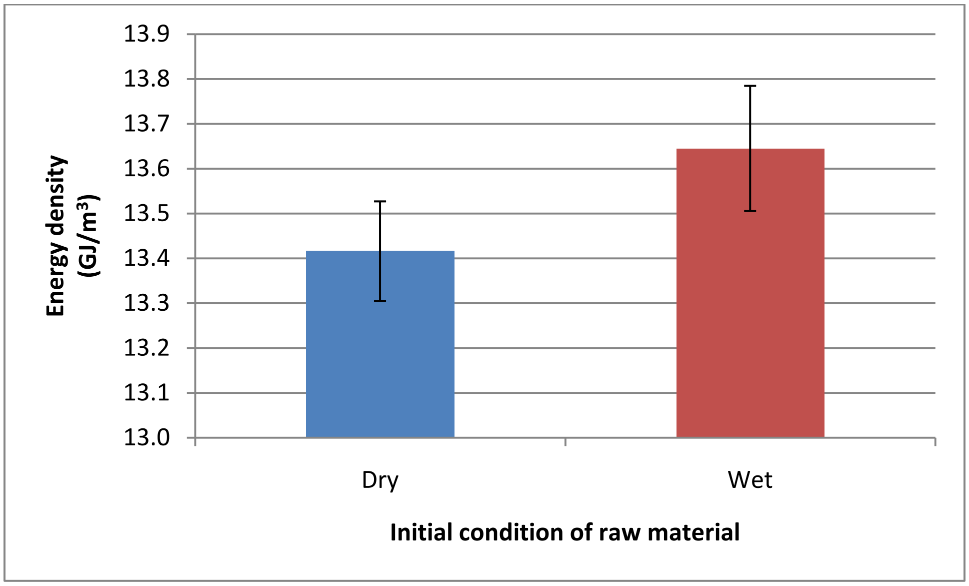

Figure 4-24: Energy density of wood briquettes sorted by the initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

On the other hand, the influence on the particle size of the material intended for densification on the energy density of briquettes was also significant (Table A 7). Results showed that energy density of the briquettes made from 3 mm particles was higher than that of briquettes made out 12-15 mm wood chips (Figure 4-25). Therefore, these results suggested that energy density of wood briquettes tended to increase as the particle size of the material intended for densification decreased. A possible explanation for these results is that it was easier for smaller particle to fill voids within the briquettes which reduced the gaps (air) among the particles.

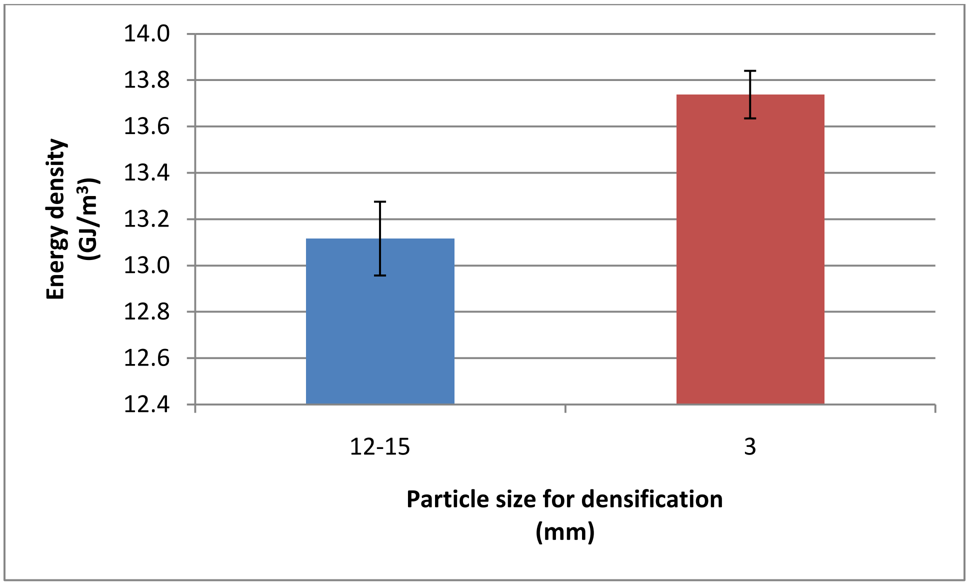

Figure 4-25: Energy density of wood briquettes sorted by the particle size of the material intended for densification (Each error bar is constructed using 1 standard error from the mean)

The interaction between the wood species from which the briquettes were made out from and the initial condition of the raw material before primary size reduction (shredding) were significant with respect to the energy density of the densified products (Table A 7). In the case of briquettes made out softwoods, the energy density of the products tended to be higher when the condition of the raw material before shredding was wet than when it was dry (Figure 4-26). However, in the case of yellow poplar, this tendency was reverse, that was, energy density of briquettes was higher when the initial condition of the material prior to primary size reduction was dry than when it was wet (Figure 4-26).

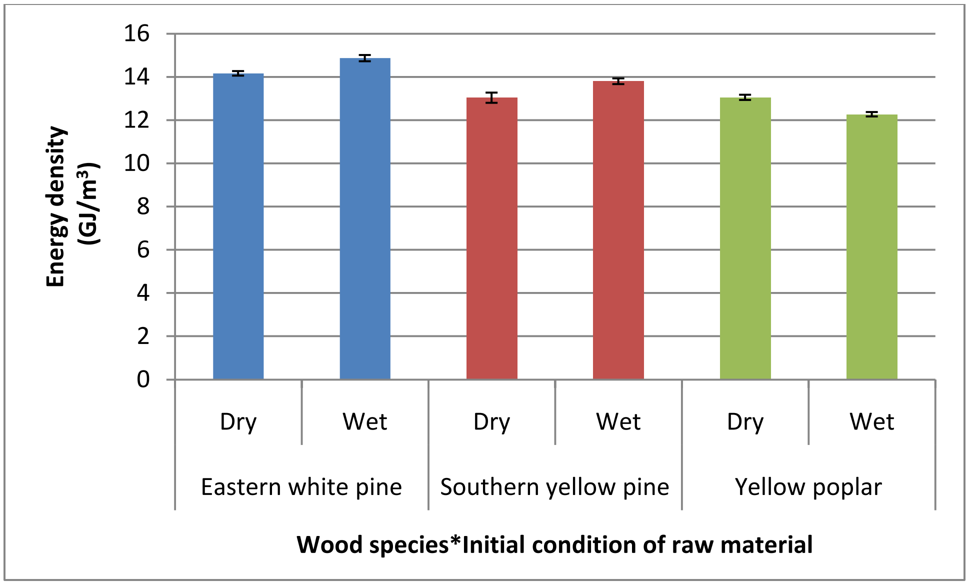

Figure 4-26: Energy density of wood briquettes sorted by wood species and initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

Similarly, the energy density of wood briquettes was significantly influenced by the interaction of initial condition of the raw material before primary size reduction and the particle size of the material intended for densification (Table A 7). From Figure 4-27, it can be observed that there was no difference in the energy density of briquettes made out of material obtained from wet lumber, regardless of the particle size of the material. However, in the case of material obtained from dry wood, energy density was higher in briquettes made from 3 mm particles than from 12-15 mm chips (Figure 4-27).

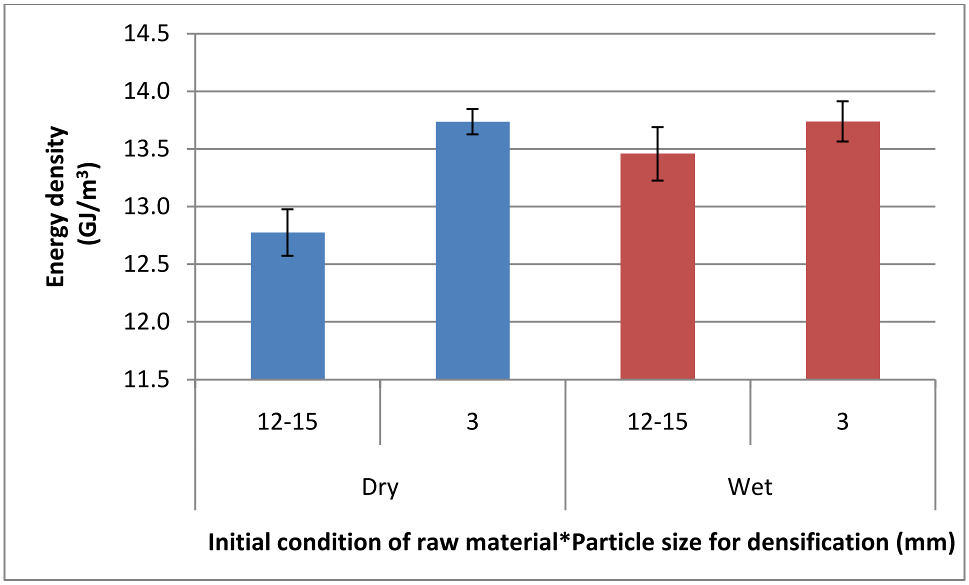

Figure 4-27: Energy density of wood briquettes sorted by initial condition of the raw material before primary size reduction and particle size of the material intended for densification (Each error bar is constructed using 1 standard error from the mean)

The three-way interaction among the factors considered in this experimentation also turned out to be significant with respect to the energy density of wood briquettes. This interaction allowed identifying maximum and minimum energy density values. For instance, maximum energy density values were attained from briquettes made out of 3 mm eastern white pine particles obtained from initially high moisture content wood (Figure 4-28). On the other hand, minimum energy density values were associated to briquettes made out 12-15 southern yellow pine chips obtained from wood that was initially dry (Figure 4-28)

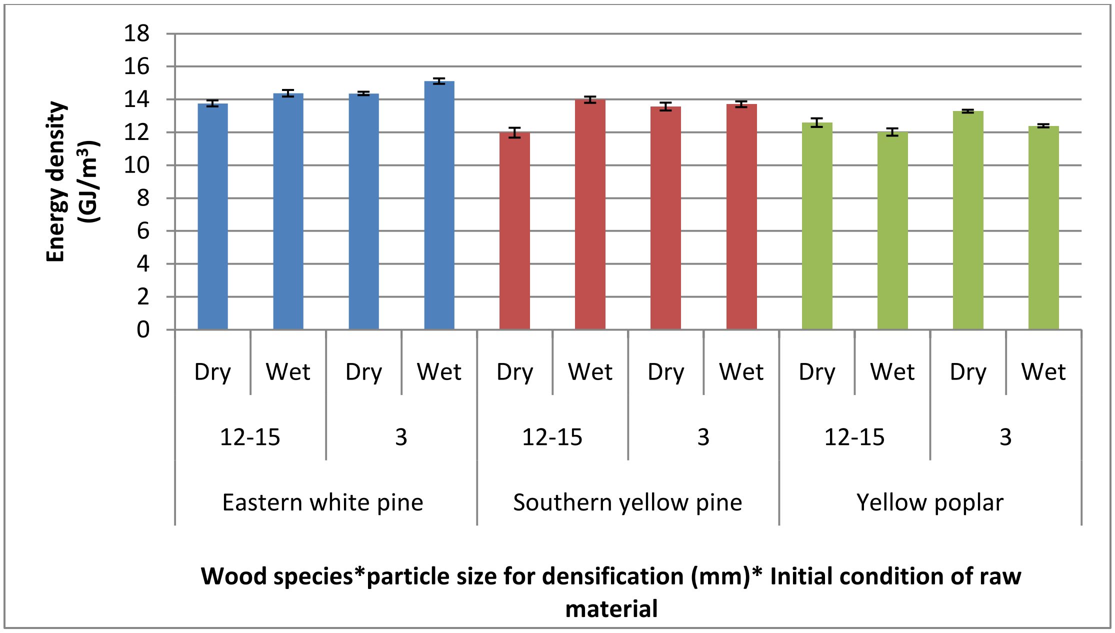

Figure 4-28: Energy density of wood briquettes sorted by wood species, particle size of the material intended for densification, and initial condition of the raw material before primary size reduction (Each error bar is constructed using 1 standard error from the mean)

It is important to mention that manufacturing of briquettes with the highest energy density demanded the highest energy consumption among all the types of briquettes evaluated in this project (Section 4.5). Alternatively, the manufacturing process to obtain briquettes that showed the lowest energy density required the minimum energy consumption among all the briquettes evaluated (Section 4.5).

CHAPTER 5

CONCLUSIONS

The main objective of this research project was the evaluation of the energy balance for the production of wood briquettes. Results obtained in this project proved that, from an energy consumption standpoint, the production of wood briquettes is feasible. Results showed that energy consumption for the production of wood briquettes was less than eight percent of the amount of energy that can be obtained from combustion of such briquettes.

This research project also included the evaluation of the energy density of wood briquettes. Results indicated that the energy density of wood briquettes was affected by several properties of the raw material such as: wood species, particle size, and moisture content.

Further conclusions attained in this research project are presented next.

5.1. **Energy requirements for production of wood briquettes**

5.1.1. <u>Energy consumption during primary size reduction (shredding)</u>

- Energy consumption for shredding of yellow poplar was higher than for shredding softwoods (eastern white pine and southern yellow pine). Moreover, there was no significant difference in the energy requirements for shredding between softwood species.

- Shredding of lumber into 12-15 mm wood chips required more energy than shredding of wood into 15-20 mm chips. It seemed the relationship between the energy requirements for shredding of wood and the particle size of the material obtained from size reduction operations were inversely proportional. A similar conclusion was reported by several authors (Hakkila, 1989); (Jones, 1981); (Cadoche and López, 1989); (Holtzapple et al., 1989).

- In the case of eastern white pine and yellow poplar, it was required more energy to comminute kiln-dried lumber than to process wet (moisture content above fiber saturation point) wood. Conversely, shredding of green southern yellow pine lumber required less energy than shredding of kiln-dried lumber

- The highest energy consumption during primary size reduction was associated with shredding of dry yellow poplar lumber to obtain 15-20 mm chips. On the other hand, the lowest energy consumption was linked to processing of wet yellow poplar lumber to obtain 12-15 mm wood chips.

- The statistical analysis showed that the main effects of all factors considered in this experimentation (wood species, particle size obtained from primary size reduction, and initial condition of the raw material) were significant with regard to the energy consumption during primary size reduction (shredding). Furthermore, interactions among factors resulted to be also significant, specifically: wood species x particle size obtained from primary size reduction, wood species x initial condition of the raw material, and wood species x particle size obtained from primary size reduction x initial condition of the raw material.

5.1.2. Energy consumption during secondary size reduction (hammermilling)

- Energy requirements for hammermilling of southern yellow pine chips were higher than those associated with hammermilling of eastern white pine and yellow poplar chips (from the primary size reduction). Moreover, energy consumption for hammermilling of eastern white pine and yellow poplar chips was similar.

- Hammermilling of 12-15 mm wood chips required less energy than hammermilling of 15-20 mm wood chips.

- Even though wet wood chips were air-dried prior to hammermilling, energy requirements for hammermilling of wood chips obtained from wet lumber were higher than those for hammermilling of chips obtained from kiln-dried lumber. This observation suggested that the initial condition of the material (dry or wet lumber) before primary size reduction (shredding) might affect the properties, shape, and/or internal structure of the chips obtained after shredding.

- The highest energy consumption during secondary size reduction was associated with hammermilling of 15-20 mm wet yellow poplar chips. On the other hand, the lowest energy consumption was related to processing of 12-15 mm dry yellow poplar chips.

- The statistical analysis showed that the main effects of all factors considered in this experimentation (wood species, chips size, and initial condition of the raw material before primary size reduction) were significant with regard to the energy consumption during secondary size reduction (hammermilling). In addition, interactions among factors resulted to be also significant, specifically: wood species x chips size and wood species x initial condition of the raw material before primary size reduction.

5.1.3. Energy consumption for drying of wood chips

- Regardless of the wood species, the thermal energy for evaporating one kilogram of water was about 3 MJ/kg H_2O. Such value was in accordance with the literature (Blankenhorn, 1980) (Wimmerstedt, 1999).

- Due to their higher initial moisture content, energy requirements for drying of eastern white pine and yellow poplar chips were almost twice as high as those of southern yellow pine chips.

5.1.4. Energy consumption for densification of wood chips and particles

- Energy requirements for densification of southern yellow pine chips and particles were the lowest among the three species considered in this experimentation. On the other hand, energy consumption for compacting of eastern white pine and yellow poplar chips and particles were similar.

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

- Energy consumption associated with densification of 3 mm wood particles was lower than that related to 12-15 mm wood chips.

- Densification of 12-15 mm wood chips obtained from wet yellow poplar lumber demanded the highest energy consumption. On the other hand, the lowest energy consumption for densification of wood chips and particles was associated with 3 mm southern yellow pine particles obtained from wet lumber.

- The statistical analysis showed that the main effects of all factors considered in this experimentation (wood species, particle size of the material intended to compact, and initial condition of the raw material before primary size reduction) were significant with regard to the energy consumption for densification of wood chips and particles. Additionally, interactions among factors resulted to be also significant, specifically: wood species x particle size of the material intended to compact, initial condition of the raw material before primary size reduction x particle size of the material intended to compact, and wood species x particle size of the material intended to compact-initial condition of the raw material before primary size reduction.

5.1.5. <u>Energy balance for production of wood briquettes</u>

- Based on the calorific value of wood, briquettes made out of softwood species (eastern white pine and southern yellow pine) provided more energy than briquettes made out of hardwood species (yellow poplar).

- The summary of the energy requirements average for each manufacturing operation involved in the production of wood briquettes was:

    - Shredding of wood: 28 KJ/o.d. kg which accounted for about 0.15 percent of the energy average in the wood species evaluated in this project.

- Hammermilling of wood chips: 173 KJ/o.d. kg which summed up to nearly one percent of the energy average in the wood species considered in this project.
- Drying wood chips: 1100 KJ/o.d. kg which represented 5.7 percent of the energy average in the wood species studied in this project.
- Densification of wood chips and particles: 88 KJ/o.d. kg which was roughly 0.5 percent of the energy average in the wood species analyzed in this project. This percentage was in accordance with the literature (Reed and Bryant, 1978).

- Maximum energy expenditure for production of wood briquettes were 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 15-20 mm wood chips, drying of wood chips, secondary size reduction (hammermilling) of such wood chips into 3 mm wood particles, and finally compaction of such wood particles. Under this manufacturing scheme, energy expenditures due to drying accounted to roughly 82 percent of the total energy consumption for production of wood briquettes. This percentage was in accordance with the literature (European Biomass Industry Association (EUBIA), 2007). On the other hand, the minimum energy requirements for production of wood briquettes was attained when dry southern yellow lumber was converted into 12-15 mm wood chips through single size reduction (shredding) and the subsequently compacted into briquettes.

- When double size reduction, drying, and densification of wood were involved in the production of wood briquettes, the overall energy consumption average represented 7.3 percent of the overall energy average of wood considered in this project. Such values were in accordance to values reported by Reed (1978).

5.2. Energy density of wood briquettes

- Briquettes made out eastern white pine exhibited the highest energy density among the wood species studied. Conversely, yellow poplar briquettes had the lowest energy density.

- Briquettes made from material that was obtained from wet lumber showed higher energy density than briquettes made out material obtained from dry lumber. Again, these results indicated that the initial moisture content of the material prior to primary size reduction (shredding) might have an effect on the properties, shape, and/or internal structure of the chips obtained after shredding.

- Briquettes made from 12-15 mm wood chips had lower energy density than briquettes made out of 3 mm wood particles.

- Briquettes made out of 3 mm eastern white pine particles obtained from initially high moisture content wood showed the highest energy density. On the other hand, briquettes made out 12-15 mm southern yellow pine chips obtained from wood that was initially dry had the lowest energy density.

- Manufacturing of the briquettes with the highest energy density required the highest amount of energy for their production. On the other hand, production of briquettes with the lowest energy density demanded the lowest energy consumption for their production.

- The statistical analysis showed that the main effects of all factors considered in this experimentation (wood species, particle size of the material intended to compact, and initial condition of the raw material before primary size reduction) were significant with regard to the energy density of wood briquettes. Additionally, interactions among factors resulted to be also statistically significant, specifically: wood species x initial condition of the raw material before primary size reduction, initial condition of the raw material before primary size reduction x particle size of the material intended to compact, and wood species x particle size of the material intended to compact x initial condition of the raw material before primary size reduction.

CHAPTER 6

RECOMMENDATIONS AND FUTURE WORK

Based on the results attained through this project, the following suggestions should be considered in future work:

- Carry out more experimentation regarding size reduction operations using different species in order to build a model capable to estimate the energy requirements for size reduction of wood based on wood properties such as: specific gravity, density, modulus of elasticity, modulus of rupture, and so on.
- Analyze the effects of fracture mechanisms of wood on other manufacturing operations for production of densified products such as: drying and densification.
- Obtain experimental data with respect to drying of wood particles in order to have experimental data of the energy requirements for drying of wood particles.
- Evaluate alternatives to optimize from an energy consumption standpoint the process of wood densification. For instance:
    - Exposure of the raw material to an air drying process before its conversion into densified products.
    - Subject only a limited amount of wood chips obtained from shredding to a secondary size reduction operation in order to reduce the energy expenditure related to size reduction.
- Evaluate strength properties of densified products in order to determine their storage and transportation capacity.

- Build an economical model to estimate the costs associated with manufacturing, transportation, and storage of densified products.
- Study combustion properties of densified products (weight loss, combustion profiles, etc) depending on their density, particle size, wood species, and so on.

CHAPTER 7

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CHAPTER 8

APPENDICES

Table A 1: JMP output from Tukey-Kramer HSD and Kruskal-Wallis tests to compare energy consumption for shredding of lumber samples with different lengths

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Level		Mean
3.6	A	43.601352
2.4	A	38.359723
1.2	A	36.500076

Levels not connected by same letter are significantly different.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
1.2	3	10.000	3.33333	-1.162
2.4	3	12.000	4.00000	-0.645
3.6	3	23.000	7.66667	1.936

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
4.3556	2	0.1133

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

Table A 2: JMP output from Tukey-Kramer HSD and Kruskal-Wallis tests to compare energy consumption for shredding of lumber samples with different widths

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Level			Mean
2	A		63.756662
4		B	49.636157
6		B	45.533056

Levels not connected by same letter are significantly different.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
2	3	24.000	8.00000	2.195
4	3	12.000	4.00000	-0.645
6	3	9.000	3.00000	-1.420

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
5.6000	2	0.0608

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

Table A 3: JMP output from Tukey-Kramer HSD and Kruskal-Wallis tests to compare energy consumption for shredding of lumber samples with different widths

Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Level			Mean
38	A		49.909739
19		B	42.490095
25.4		B	42.091992

Levels not connected by same letter are significantly different.

Wilcoxon / Kruskal-Wallis Tests (Rank Sums)

Level	Count	Score Sum	Score Mean	(Mean-Mean0)/Std0
19	3	10.000	3.33333	-1.162
25.4	3	11.000	3.66667	-0.904
38	3	24.000	8.00000	2.195

1-way Test, ChiSquare Approximation

ChiSquare	DF	Prob>ChiSq
5.4222	2	0.0665

Small sample sizes. Refer to statistical tables for tests, rather than large-sample approximations.

Table A 4: JMP output of the full factorial ANOVA with interactions for primary size reduction (shredding)

Response Net Energy per unit of ovendry mass (kJ/kg)

Whole Model

Summary of Fit

RSquare	0.582598
RSquare Adj	0.57787
Root Mean Square Error	4.872543
Mean of Response	27.73319
Observations (or Sum Wgts)	983

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	32177.023	2925.18	123.2088
Error	971	23053.169	23.74	Prob > F
C. Total	982	55230.193		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	28.283149	0.157788	179.25	0.0000*
Wood Species[Eastern white pine]	-1.113032	0.218325	-5.10	<.0001*
Wood Species[Southern yellow pine]	-1.930245	0.225926	-8.54	<.0001*
Particle size from primary size reduction (mm)[12-15]	0.3900933	0.157788	2.47	0.0136*
Wood Species[Eastern white pine]*Particle size from primary size reduction (mm)[12-15]	0.5958145	0.218325	2.73	0.0065*
Wood Species[Southern yellow pine]*Particle size from primary size reduction (mm)[12-15]	0.1628755	0.225926	0.72	0.4711
Initial condition[Dry]	2.7468627	0.157788	17.41	<.0001*
Wood Species[Eastern white pine]*Initial condition[Dry]	-0.412277	0.218325	-1.89	0.0593
Wood Species[Southern yellow pine]*Initial condition[Dry]	-5.679004	0.225926	-25.14	<.0001*
Particle size from primary size reduction (mm)[12-15]*Initial condition[Dry]	-0.254291	0.157788	-1.61	0.1074
Wood Species[Eastern white pine]*Particle size from primary size reduction (mm)[12-15]*Initial condition[Dry]	-0.509758	0.218325	-2.33	0.0198*
Wood Species[Southern yellow pine]*Particle size from primary size reduction (mm)[12-15]*Initial condition[Dry]	-0.019	0.225926	-0.08	0.9330

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wood Species	2	2	4400.432	92.6731	<.0001*
Particle size from primary size reduction (mm)	1	1	145.112	6.1121	0.0136*
Wood Species*Particle size from primary size reduction (mm)	2	2	307.568	6.4774	0.0016*
Initial condition	1	1	7195.140	303.0595	<.0001*
Wood Species*Initial condition	2	2	21212.573	446.7370	<.0001*
Particle size from primary size reduction (mm)*Initial condition	1	1	61.663	2.5973	0.1074
Wood Species*Particle size from primary size reduction (mm)*Initial condition	2	2	175.824	3.7029	0.0250*

Wood Species

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Eastern white pine	27.170117	0.26135521	26.6363
Southern yellow pine	26.352905	0.28006628	26.5458
Poplar	31.326427	0.27808064	30.1691

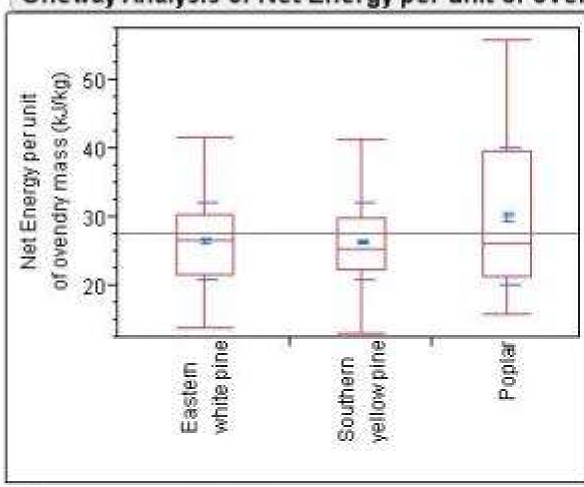
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.34731

Level			Least Sq Mean
Poplar	A		31.326427
Eastern white pine		B	27.170117
Southern yellow pine		B	26.352905

Levels not connected by same letter are significantly different.

Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Wood Species



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Eastern white pine	366	26.6363	5.6376	0.29468	26.057	27.216
Southern yellow pine	304	26.5458	5.6417	0.32357	25.909	27.183
Poplar	313	30.1691	10.0096	0.56577	29.056	31.282

Particle size from primary size reduction (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
12-15	28.673243	0.22473917	28.1118
15-20	27.893056	0.22154026	27.3630

LSMeans Differences Student's t

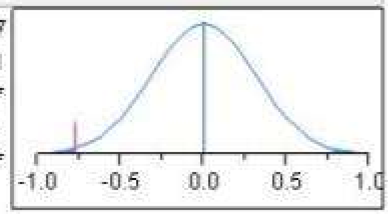
α= 0.050 t= 1.96241

Level			Least Sq Mean
12-15	A		28.673243
15-20		B	27.893056

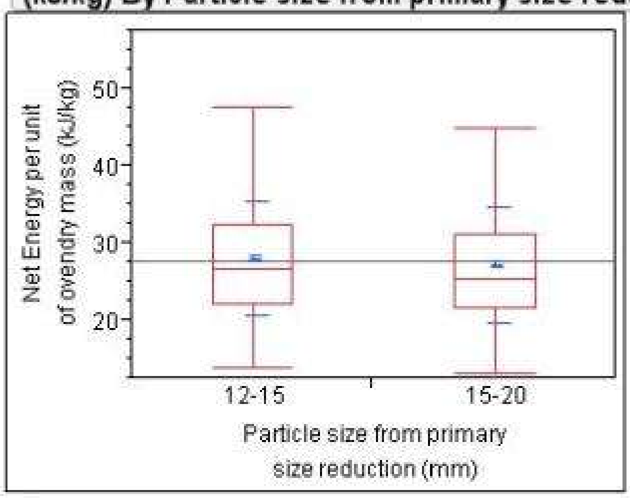
Levels not connected by same letter are significantly different.

Comparing 15-20 with 12-15

Difference	-0.7802	t Ratio	-2.47227
Std Err Dif	0.3156	DF	971
Upper CL Dif	-0.1609	Prob > |t|	0.0136*
Lower CL Dif	-1.3995	Prob > t	0.9932
Confidence	0.95	Prob < t	0.0068*



Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Particle size from primary size reduction (mm)



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
12-15	486	28.1118	7.48571	0.33956	27.445	28.779
15-20	497	27.3630	7.50202	0.33651	26.702	28.024

Initial condition

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	31.030012	0.23795432	30.9003
Wet	25.536287	0.20728127	25.3705

LSMeans Differences Student's t

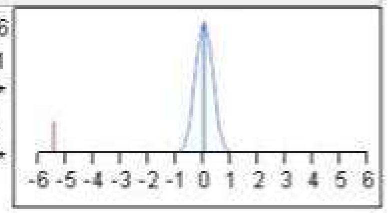
α= 0.050 t= 1.96241

Level		Least Sq Mean
Dry	A	31.030012
Wet	B	25.536287

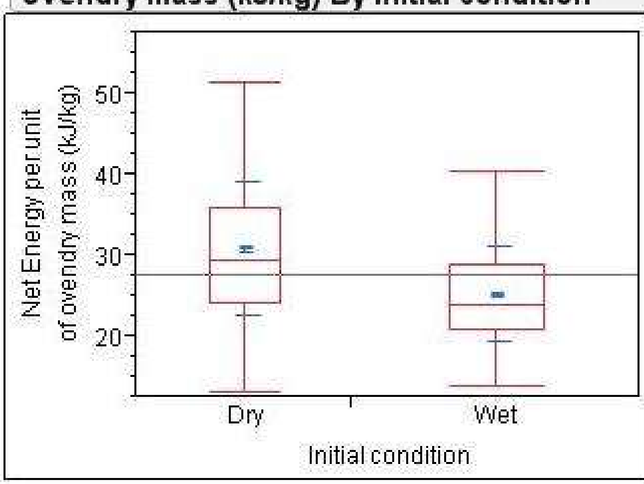
Levels not connected by same letter are significantly different.

Comparing Wet with Dry

Difference	-5.4937	t Ratio	-17.4086
Std Err Dif	0.3156	DF	971
Upper CL Dif	-4.8744	Prob > |t|	0.0000*
Lower CL Dif	-6.1130	Prob > t	1.0000
Confidence	0.95	Prob < t	0.0000*



Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Initial condition



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Dry	420	30.9003	8.26203	0.40315	30.108	31.693
Wet	563	25.3705	5.85613	0.24681	24.886	25.855

Wood Species*Particle size from primary size reduction (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,12-15	28.156025	0.37183861
Eastern white pine,15-20	26.184209	0.36737204
Southern yellow pine,12-15	26.905873	0.39607353
Southern yellow pine,15-20	25.799936	0.39607353
Poplar,12-15	30.957830	0.39928816
Poplar,15-20	31.695023	0.38714898

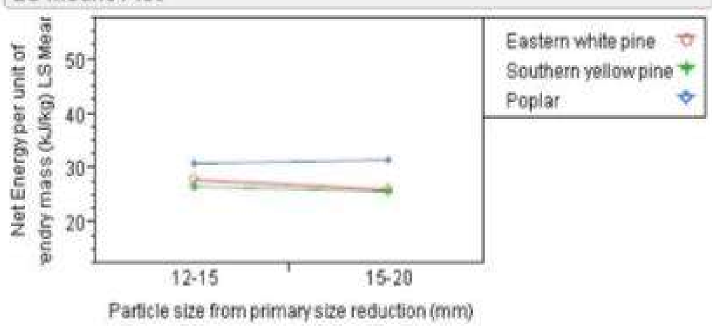
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.85543

Level			Least Sq Mean
Poplar,15-20	A		31.695023
Poplar,12-15	A		30.957830
Eastern white pine,12-15	B		28.156025
Southern yellow pine,12-15	B	C	26.905873
Eastern white pine,15-20		C	26.184209
Southern yellow pine,15-20		C	25.799936

Levels not connected by same letter are significantly different.

LS Means Plot



Wood Species*Initial condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,Dry	29.504702	0.40893531
Eastern white pine,Wet	24.835532	0.32557347
Southern yellow pine,Dry	23.420763	0.40889475
Southern yellow pine,Wet	29.285046	0.38282315
Poplar,Dry	40.164571	0.41854189
Poplar,Wet	22.488283	0.36624863

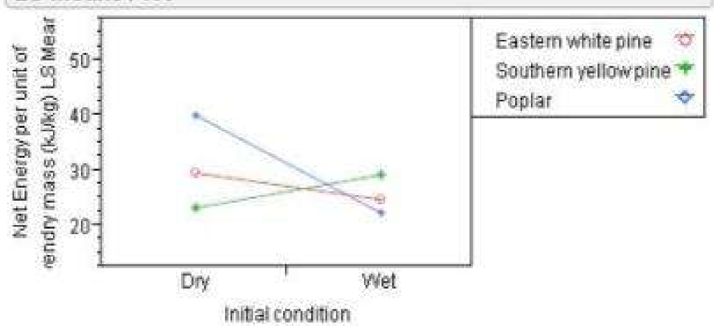
LSMeans Differences Tukey HSD

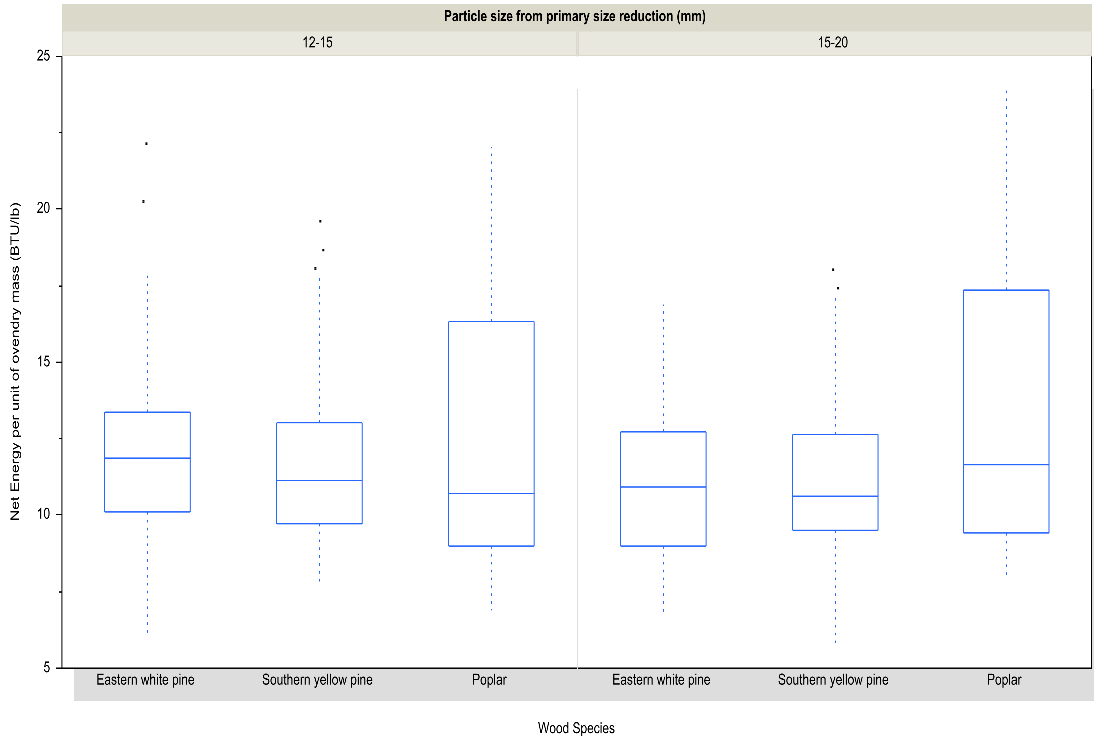
α= 0.050 Q= 2.85543

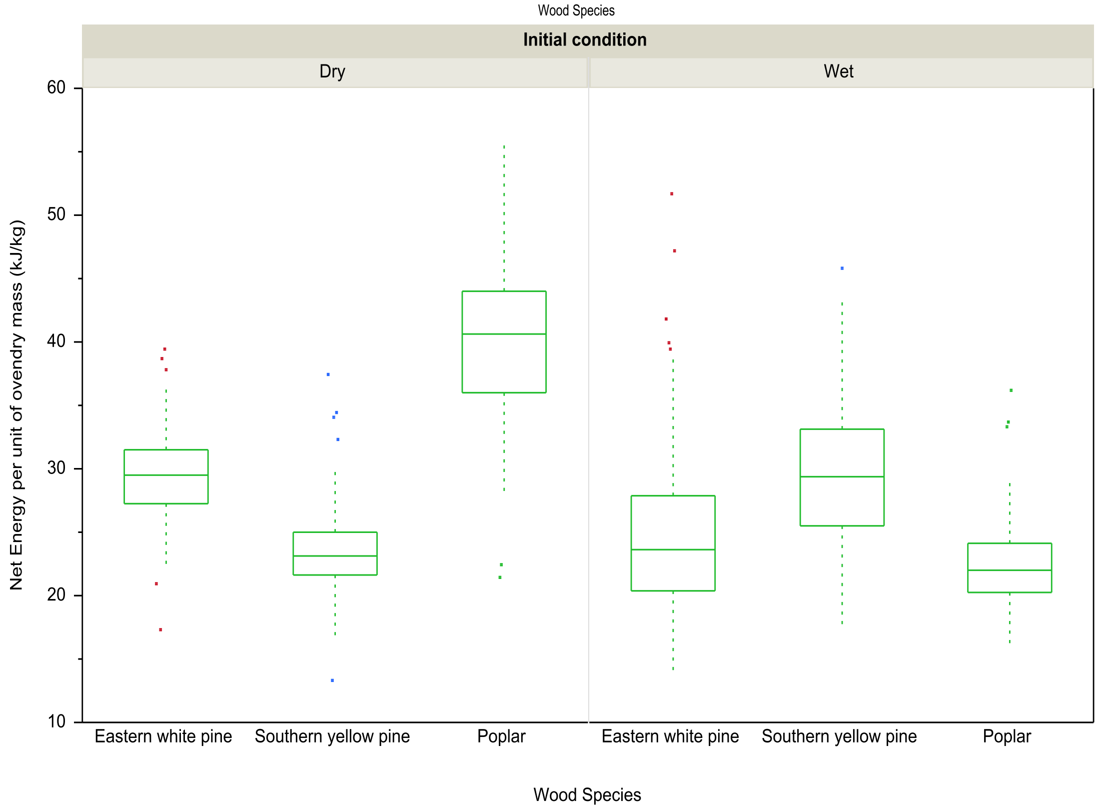
Level					Least Sq Mean
Poplar,Dry	A				40.164571
Eastern white pine,Dry		B			29.504702
Southern yellow pine,Wet		B			29.285046
Eastern white pine,Wet			C		24.835532
Southern yellow pine,Dry			C	D	23.420763
Poplar,Wet				D	22.488283

Levels not connected by same letter are significantly different.

LS Means Plot




Particle size from primary size reduction (mm)
12-15
15-20
Net Energy per unit of ovendry mass (BTU/lb)
25
20
15
10
5
Eastern white pine
Southern yellow pine
Poplar
Eastern white pine
Southern yellow pine
Poplar
Wood Species


Initial condition
Dry
Wet
Net Energy per unit of ovendry mass (kJ/kg)
60
50
40
30
20
10
Eastern white pine
Southern yellow pine
Poplar
Eastern white pine
Southern yellow pine
Poplar
Wood Species

Wood Species*Particle size from primary size reduction (mm)*Initial condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,12-15,Dry	29.726561	0.58238031
Eastern white pine,12-15,Wet	26.585488	0.46248134
Eastern white pine,15-20,Dry	29.282844	0.57423473
Eastern white pine,15-20,Wet	23.085575	0.45837031
Southern yellow pine,12-15,Dry	23.700441	0.57826450
Southern yellow pine,12-15,Wet	30.111306	0.54139370
Southern yellow pine,15-20,Dry	23.141085	0.57826450
Southern yellow pine,15-20,Wet	28.458786	0.54139370
Poplar,12-15,Dry	40.070441	0.60906791
Poplar,12-15,Wet	21.845219	0.51648855
Poplar,15-20,Dry	40.258701	0.57423473
Poplar,15-20,Wet	23.131346	0.51941486

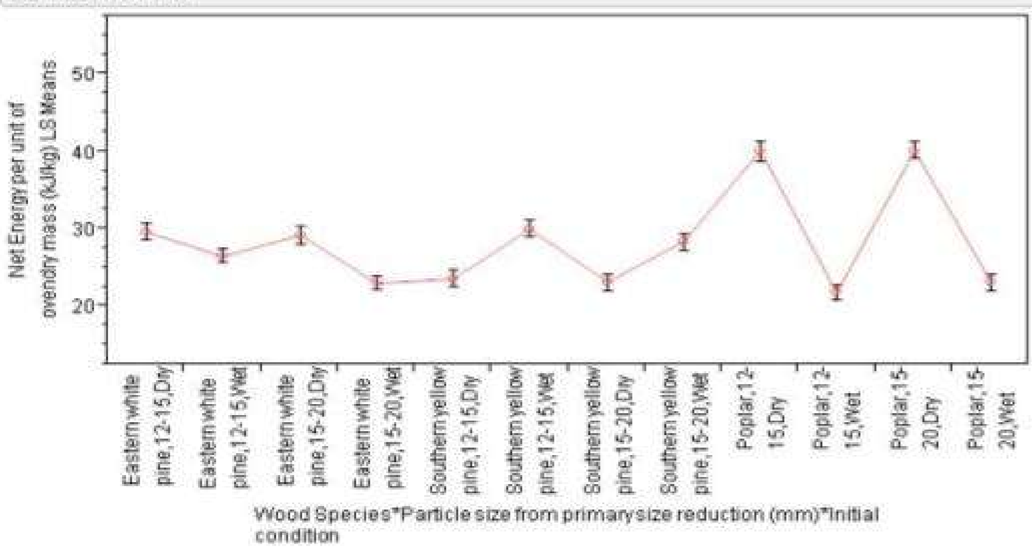
LSMeans Differences Tukey HSD

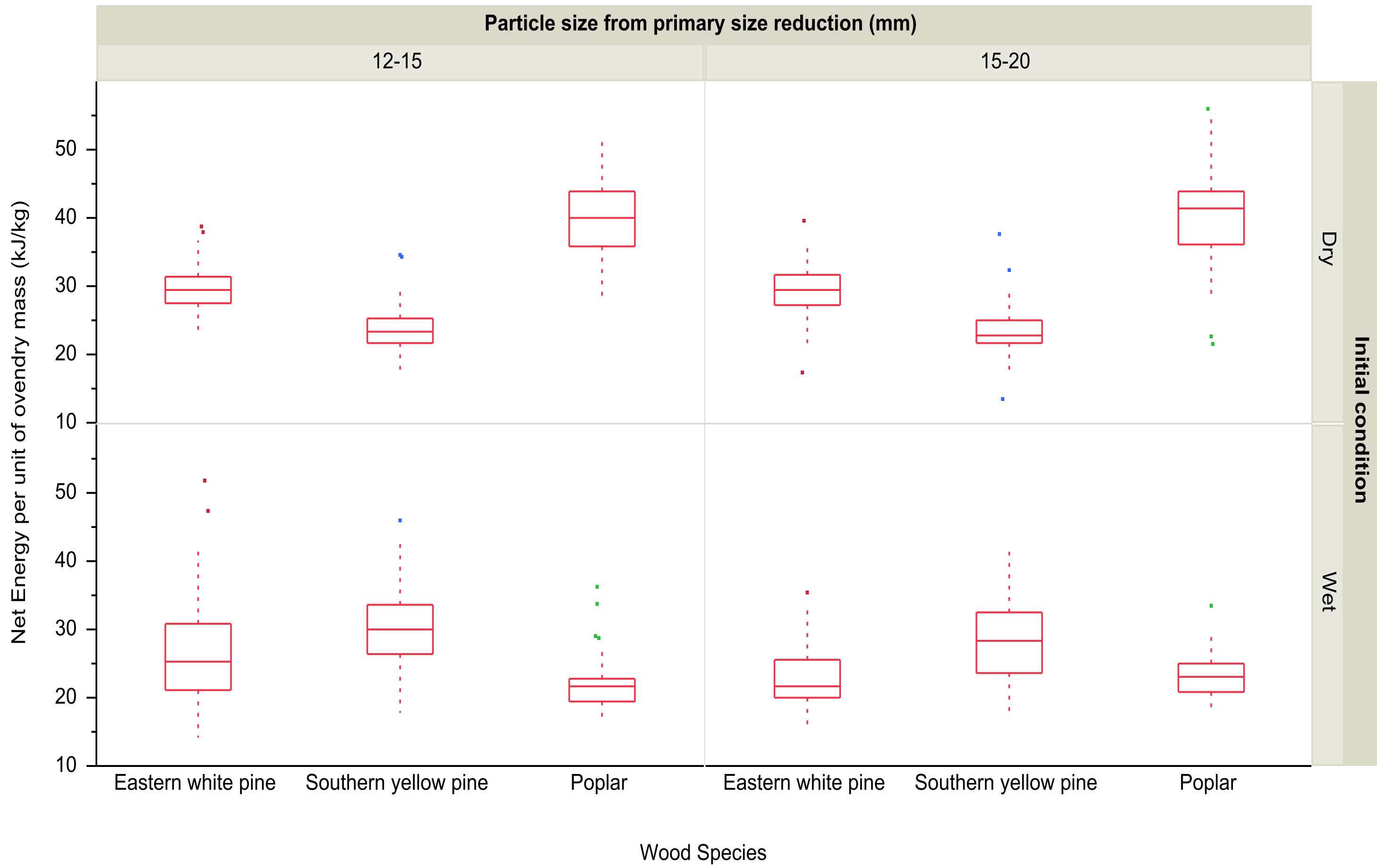
α= 0.050 Q= 3.27606

Level					Least Sq Mean
Poplar,15-20,Dry	A				40.258701
Poplar,12-15,Dry	A				40.070441
Southern yellow pine,12-15,Wet		B			30.111306
Eastern white pine,12-15,Dry		B			29.726561
Eastern white pine,15-20,Dry		B			29.282844
Southern yellow pine,15-20,Wet		B	C		28.458786
Eastern white pine,12-15,Wet			C		26.585488
Southern yellow pine,12-15,Dry				D	23.700441
Southern yellow pine,15-20,Dry				D	23.141085
Poplar,15-20,Wet				D	23.131346
Eastern white pine,15-20,Wet				D	23.085575
Poplar,12-15,Wet				D	21.845219

Levels not connected by same letter are significantly different.

LS Means Plot





Particle size from primary size reduction (mm)
12-15
15-20
Net Energy per unit of ovendry mass (kJ/kg)
50
40
30
20
10
Dry
Wet
Initial condition
Eastern white pine
Southern yellow pine
Poplar
Wood Species

Table A 5: JMP output of the full factorial ANOVA with interactions for secondary size reduction (hammermilling)

Response Net Energy per unit of ovendry mass (kJ/kg)

Whole Model

Summary of Fit

RSquare	0.550648
RSquare Adj	0.496331
Root Mean Square Error	22.45635
Mean of Response	172.9197
Observations (or Sum Wgts)	103

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	56235.15	5112.29	10.1376
Error	91	45890.20	504.29	Prob > F
C. Total	102	102125.35		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	172.97749	2.219555	77.93	<.0001*
Wood Species[Eastern white pine]	-5.302068	3.097702	-1.71	0.0904
Wood Species[Southern yellow pine]	13.701186	3.174145	4.32	<.0001*
Chips size (mm)[12-15]	-7.914962	2.219555	-3.57	0.0006*
Wood Species[Eastern white pine]*Chips size (mm)[12-15]	-0.888566	3.097702	-0.29	0.7754
Wood Species[Southern yellow pine]*Chips size (mm)[12-15]	7.3865597	3.174145	2.33	0.0222*
Initial condition before primary size reduction[Dry]	-17.04227	2.219555	-7.68	<.0001*
Wood Species[Eastern white pine]*Initial condition before primary size reduction[Dry]	3.6792391	3.097702	1.19	0.2380
Wood Species[Southern yellow pine]*Initial condition before primary size reduction[Dry]	8.1961422	3.174145	2.58	0.0114*
Chips size (mm)[12-15]*Initial condition before primary size reduction[Dry]	-1.438333	2.219555	-0.65	0.5192
Wood Species[Eastern white pine]*Chips size (mm)[12-15]*Initial condition before primary size reduction[Dry]	-1.007755	3.097702	-0.33	0.7457
Wood Species[Southern yellow pine]*Chips size (mm)[12-15]*Initial condition before primary size reduction[Dry]	1.8033126	3.174145	0.57	0.5713

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wood Species	2	2	9523.262	9.4423	0.0002*
Chips size (mm)	1	1	6412.753	12.7165	0.0006*
Wood Species*Chips size (mm)	2	2	3239.947	3.2124	0.0449*
Initial condition before primary size reduction	1	1	29730.454	58.9553	<.0001*
Wood Species*Initial condition before primary size reduction	2	2	7458.691	7.3953	0.0011*
Chips size (mm)*Initial condition before primary size reduction	1	1	211.182	0.4188	0.5192
Wood Species*Chips size (mm)*Initial condition before primary size reduction	2	2	163.988	0.1626	0.8502

Wood Species

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Eastern white pine	167.67543	3.7427258	167.675
Southern yellow pine	186.67868	3.9301803	186.361
Poplar	164.57838	3.8579134	165.426

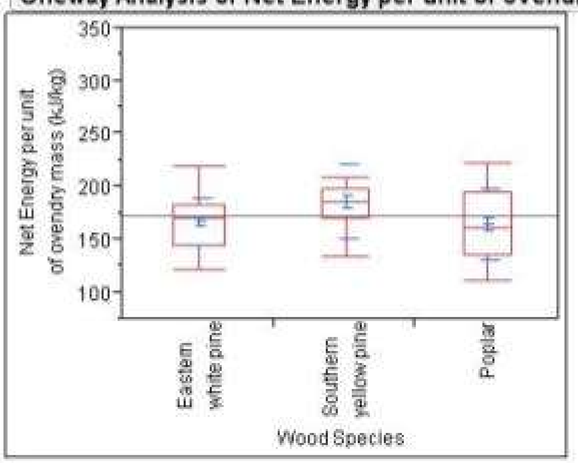
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.38268

Level			Least Sq Mean
Southern yellow pine	A		186.67868
Eastern white pine		B	167.67543
Poplar		B	164.57838

Levels not connected by same letter are significantly different.

Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Wood Species



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Eastern white pine	36	167.675	22.2630	3.7105	160.14	175.21
Southern yellow pine	33	186.361	34.5900	6.0213	174.10	198.63
Poplar	34	165.426	33.7681	5.7912	153.64	177.21

Chips size (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
12-15	165.06253	3.1499731	165.400
15-20	180.89246	3.1278367	180.295

LSMeans Differences Student's t

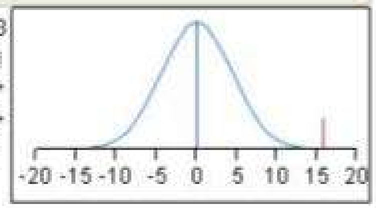
α= 0.050 t= 1.98638

Level			Least Sq Mean
15-20	A		180.89246
12-15		B	165.06253

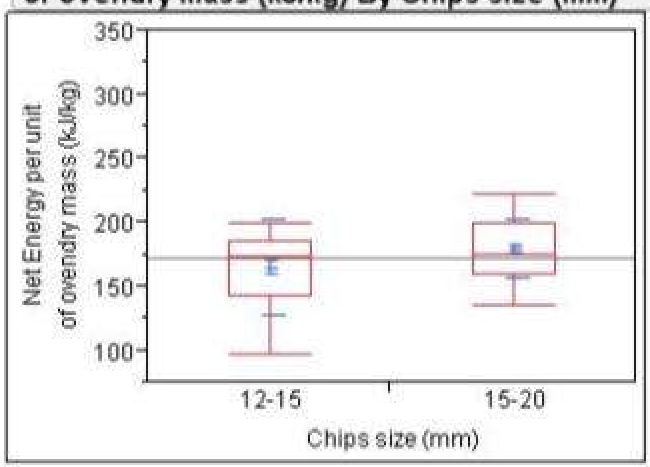
Levels not connected by same letter are significantly different.

Comparing 15-20 with 12-15

Difference	15.8299	t Ratio	3.566013
Std Err Dif	4.4391	DF	91
Upper CL Dif	24.6477	Prob > |t|	0.0006*
Lower CL Dif	7.0122	Prob > t	0.0003*
Confidence	0.95	Prob < t	0.9997



Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Chips size (mm)



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
12-15	51	165.400	37.4734	5.2473	154.86	175.94
15-20	52	180.295	22.6654	3.1431	173.99	186.61

Initial condition before primary size reduction

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	155.93523	3.1189382	156.227
Wet	190.01976	3.1587843	189.939

LSMeans Differences Student's t

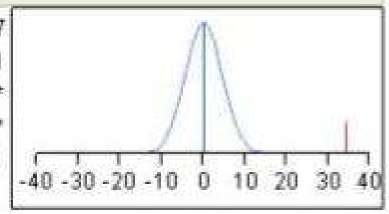
α= 0.050 t= 1.98638

Level			Least Sq Mean
Wet	A		190.01976
Dry		B	155.93523

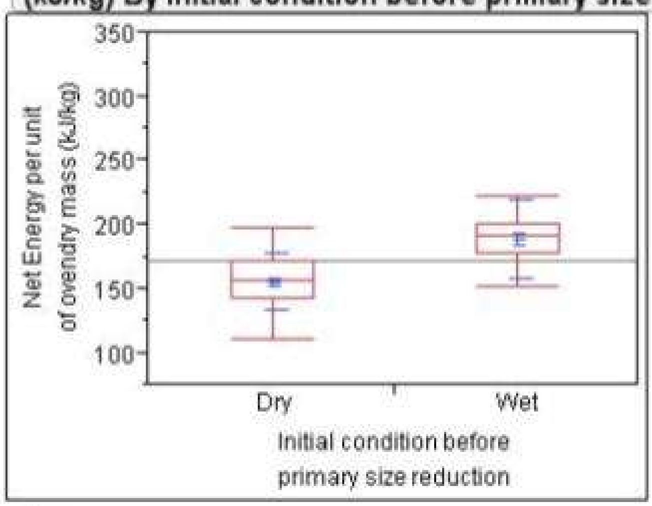
Levels not connected by same letter are significantly different.

Comparing Wet with Dry

Difference	34.0845	t Ratio	7.678237
Std Err Dif	4.4391	DF	91
Upper CL Dif	42.9023	Prob > |t|	<.0001*
Lower CL Dif	25.2668	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000



Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Initial condition before primary size reduction



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Dry	52	156.227	22.3183	3.0950	150.01	162.44
Wet	51	189.939	30.8089	4.3141	181.27	198.60

Wood Species*Chips size (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,12-15	158.87390	5.2930136
Eastern white pine,15-20	176.47695	5.2930136
Southern yellow pine,12-15	186.15028	5.4559135
Southern yellow pine,15-20	187.20708	5.6584695
Poplar,12-15	150.16342	5.6140887
Poplar,15-20	178.99333	5.2930136

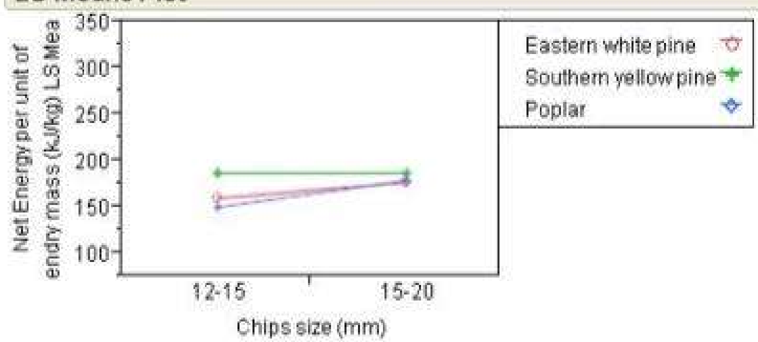
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.91134

Level				Least Sq Mean
Southern yellow pine,15-20	A			187.20708
Southern yellow pine,12-15	A			186.15028
Poplar,15-20	A	B		178.99333
Eastern white pine,15-20	A	B		176.47695
Eastern white pine,12-15		B	C	158.87390
Poplar,12-15			C	150.16342

Levels not connected by same letter are significantly different.

LS Means Plot



Wood Species*Initial condition before primary size reduction

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,Dry	154.31240	5.2930136
Eastern white pine,Wet	181.03845	5.2930136
Southern yellow pine,Dry	177.83255	5.4559135
Southern yellow pine,Wet	195.52481	5.6584695
Poplar,Dry	135.66073	5.4559135
Poplar,Wet	193.49603	5.4559135

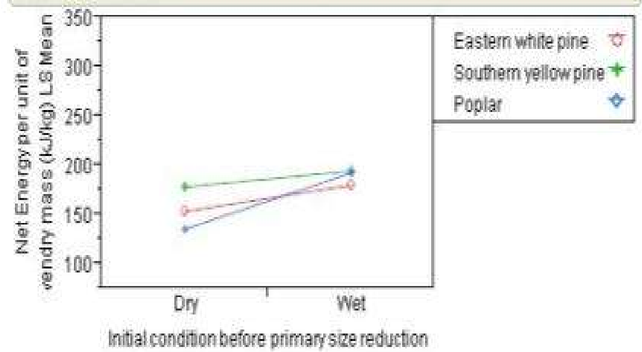
LSMeans Differences Tukey HSD

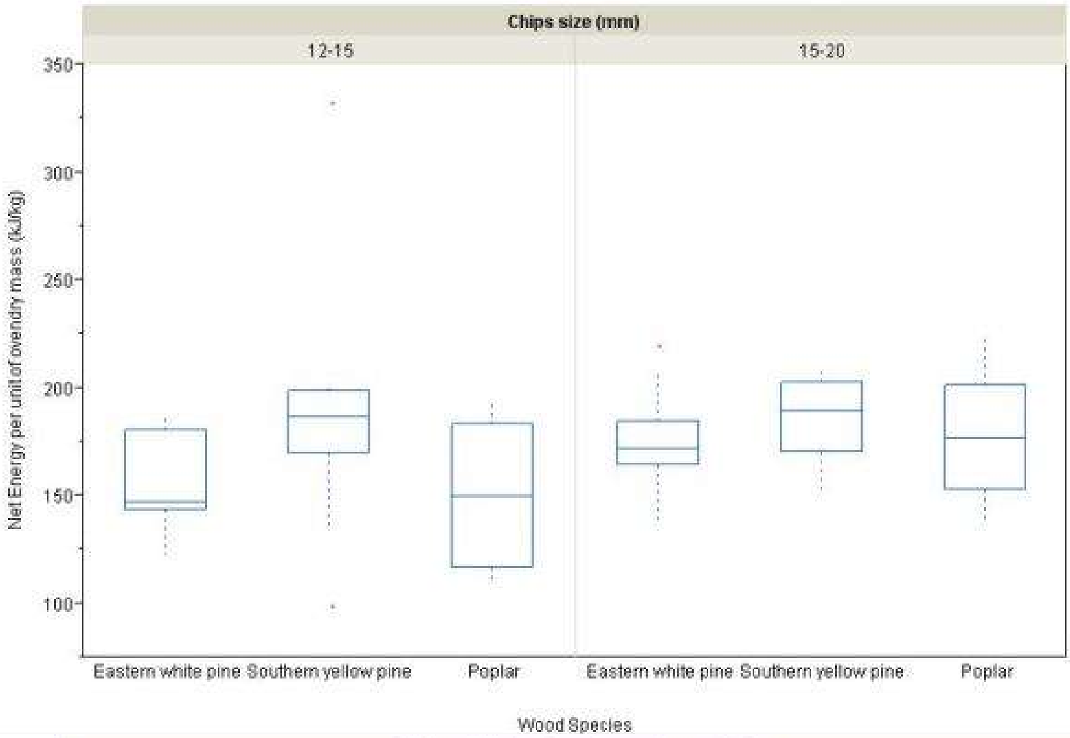
α= 0.050 Q= 2.91134

Level			Least Sq Mean
Southern yellow pine,Wet	A		195.52481
Poplar,Wet	A		193.49603
Eastern white pine,Wet	A		181.03845
Southern yellow pine,Dry	A		177.83255
Eastern white pine,Dry		B	154.31240
Poplar,Dry		B	135.66073

Levels not connected by same letter are significantly different.

LS Means Plot




Chips size (mm)
12-15
15-20
Net Energy per unit of ovendry mass (kJ/kg)
350
300
250
200
150
100
Eastern white pine
Southern yellow pine
Poplar
Eastern white pine
Southern yellow pine
Poplar
Wood Species

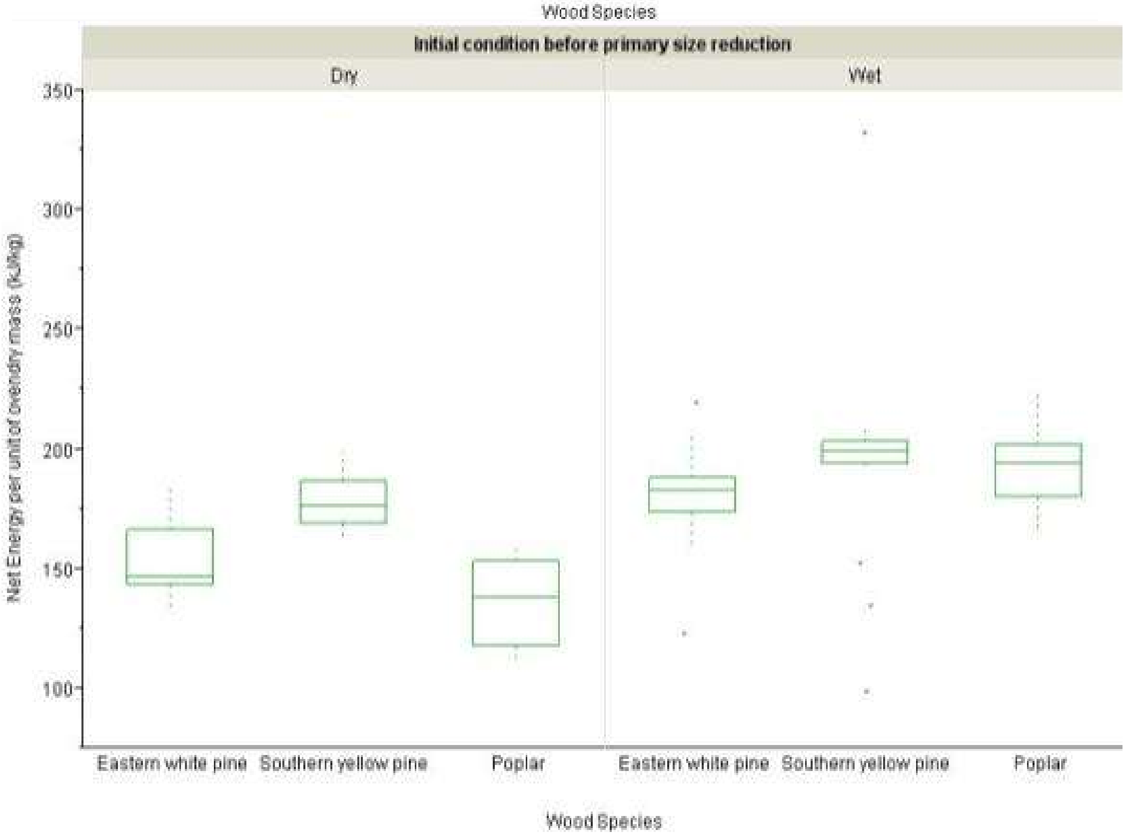

Initial condition before primary size reduction
Dry
Wet
Net Energy per unit of ovendry mass (kJ/kg)
350
300
250
200
150
100
Eastern white pine
Southern yellow pine
Poplar
Eastern white pine
Southern yellow pine
Poplar
Wood Species

Table A 6: JMP output of the full factorial ANOVA with interactions for densification

Whole Model

Summary of Fit

RSquare	0.895116
RSquare Adj	0.866272
Root Mean Square Error	8.88429
Mean of Response	88.74512
Observations (or Sum Wgts)	52

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	26944.707	2449.52	31.0338
Error	40	3157.224	78.93	Prob > F
C. Total	51	30101.931		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	94.750431	1.324392	71.54	<.0001*
Wood Species[Eastern white pine]	1.2455085	1.843475	0.68	0.5032
Wood Species[Southern yellow pine]	-8.117489	1.930616	-4.20	0.0001*
Initial condition[Dry]	-3.69214	1.324392	-2.79	0.0081*
Wood Species[Eastern white pine]*Initial condition[Dry]	-0.632073	1.843475	-0.34	0.7335
Wood Species[Southern yellow pine]*Initial condition[Dry]	-7.400004	1.930616	-3.83	0.0004*
Particle size for briquetting[12-15 mm]	19.483068	1.324392	14.71	<.0001*
Wood Species[Eastern white pine]*Particle size for briquetting[12-15 mm]	2.9795013	1.843475	1.62	0.1139
Wood Species[Southern yellow pine]*Particle size for briquetting[12-15 mm]	2.6671908	1.930616	1.38	0.1748
Initial condition[Dry]*Particle size for briquetting[12-15 mm]	-3.509316	1.324392	-2.65	0.0115*
Wood Species[Eastern white pine]*Initial condition[Dry]*Particle size for briquetting[12-15 mm]	6.6844767	1.843475	3.63	0.0008*
Wood Species[Southern yellow pine]*Initial condition[Dry]*Particle size for briquetting[12-15 mm]	1.8286573	1.930616	0.95	0.3492

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wood Species	2	2	1648.652	10.4437	0.0002*
Initial condition	1	1	613.435	7.7718	0.0081*
Wood Species*Initial condition	2	2	1760.165	11.1501	0.0001*
Particle size for briquetting	1	1	17081.546	216.4122	<.0001*
Wood Species*Particle size for briquetting	2	2	745.937	4.7253	0.0144*
Initial condition*Particle size for briquetting	1	1	554.188	7.0212	0.0115*
Wood Species*Initial condition*Particle size for briquetting	2	2	1918.553	12.1534	<.0001*

Wood Species

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Eastern white pine	95.99594	2.2210725	88.5084
Southern yellow pine	86.63294	2.4330630	79.7131
Yellow poplar	101.62241	2.2210725	97.0103

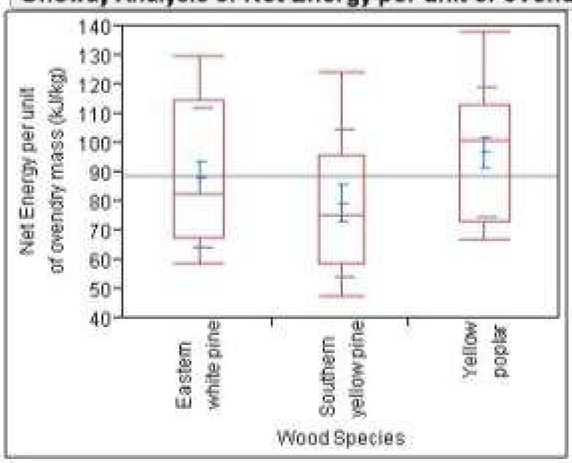
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.43392

Level			Least Sq Mean
Yellow poplar	A		101.62241
Eastern white pine	A		95.99594
Southern yellow pine		B	86.63294

Levels not connected by same letter are significantly different.

Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Wood Species



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Eastern white pine	18	88.5084	23.8881	5.6305	76.629	100.39
Southern yellow pine	16	79.7131	25.1176	6.2794	66.329	93.10
Yellow poplar	18	97.0103	22.2311	5.2399	85.955	108.07

Initial condition

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Dry	91.058291	1.9306161	86.5491
Wet	98.442571	1.8134981	90.7784

LSMeans Differences Student's t

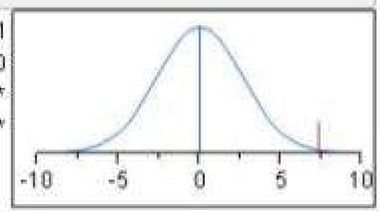
α= 0.050 t= 2.02108

Level			Least Sq Mean
Wet	A		98.442571
Dry		B	91.058291

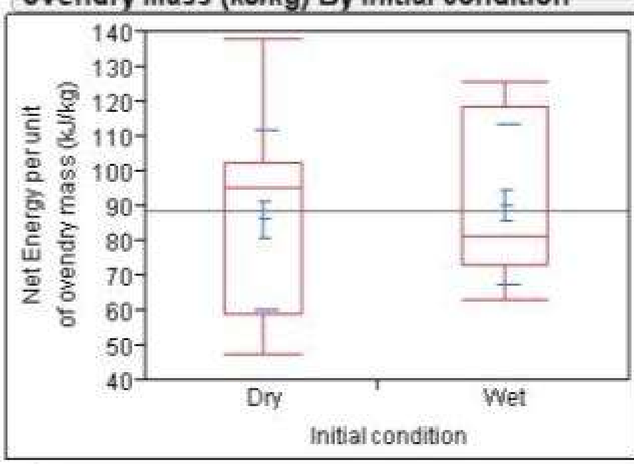
Levels not connected by same letter are significantly different.

Comparing Wet with Dry

Difference	7.3843	t Ratio	2.787801
Std Err Dif	2.6488	DF	40
Upper CL Dif	12.7377	Prob > |t|	0.0081*
Lower CL Dif	2.0309	Prob > t	0.0040*
Confidence	0.95	Prob < t	0.9960



Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Initial condition



Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Dry	25	86.5491	25.9471	5.1894	75.839	97.260
Wet	27	90.7784	22.9646	4.4195	81.694	99.863

Particle size for briquetting

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
12-15 mm	114.23350	2.1795534	115.305
3 mm	75.26736	1.5051913	75.844

LSMeans Differences Student's t

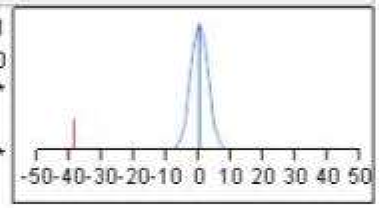
α= 0.050 t= 2.02108

Level			Least Sq Mean
12-15 mm	A		114.23350
3 mm		B	75.26736

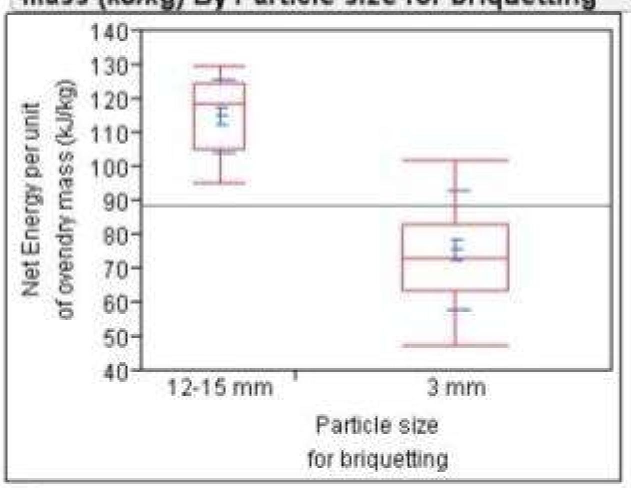
Levels not connected by same letter are significantly different.

Comparing 3 mm with 12-15 mm

Difference	-38.966	t Ratio	-14.711
Std Err Dif	2.649	DF	40
Upper CL Dif	-33.613	Prob > |t|	0.0000*
Lower CL Dif	-44.320	Prob > t	1.0000
Confidence	0.95	Prob < t	0.0000*



Oneway Analysis of Net Energy per unit of ovendry mass (kJ/kg) By Particle size for briquetting



Means and Std Deviations

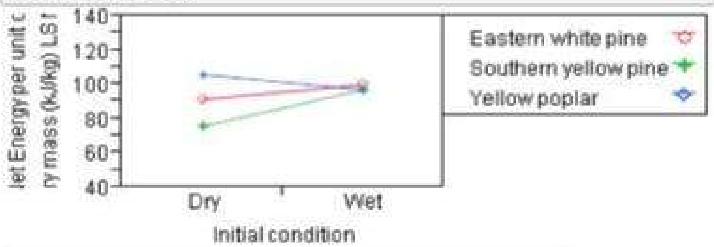
Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
12-15 mm	17	115.305	10.7271	2.6017	109.79	120.82
3 mm	35	75.844	17.5257	2.9624	69.82	81.86

Wood Species*Initial condition

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,Dry	91.67173	3.1410708
Eastern white pine,Wet	100.32015	3.1410708
Southern yellow pine,Dry	75.54080	3.7165651
Southern yellow pine,Wet	97.72509	3.1410708
Yellow poplar,Dry	105.96235	3.1410708
Yellow poplar,Wet	97.28248	3.1410708

LS Means Plot



LSMeans Differences Tukey HSD

α= 0.050 Q= 2.99223

Level				Least Sq Mean
Yellow poplar,Dry	A			105.96235
Eastern white pine,Wet	A	B		100.32015
Southern yellow pine,Wet	A	B		97.72509
Yellow poplar,Wet	A	B		97.28248
Eastern white pine,Dry		B		91.67173
Southern yellow pine,Dry			C	75.54080

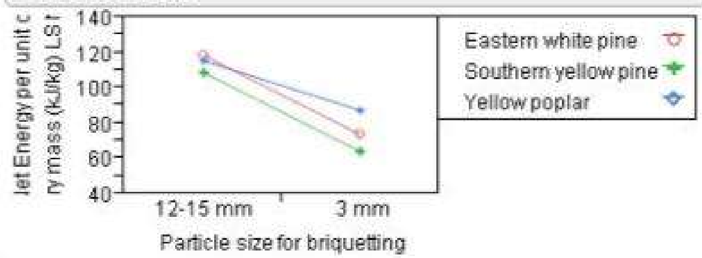
Levels not connected by same letter are significantly different.

Wood Species*Particle size for briquetting

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,12-15 mm	118.45851	3.6269962
Eastern white pine,3 mm	73.53337	2.5646736
Southern yellow pine,12-15 mm	108.78320	4.0551050
Southern yellow pine,3 mm	64.48268	2.6898523
Yellow poplar,12-15mm	115.45879	3.6269962
Yellow poplar,3 mm	87.78604	2.5646736

LS Means Plot

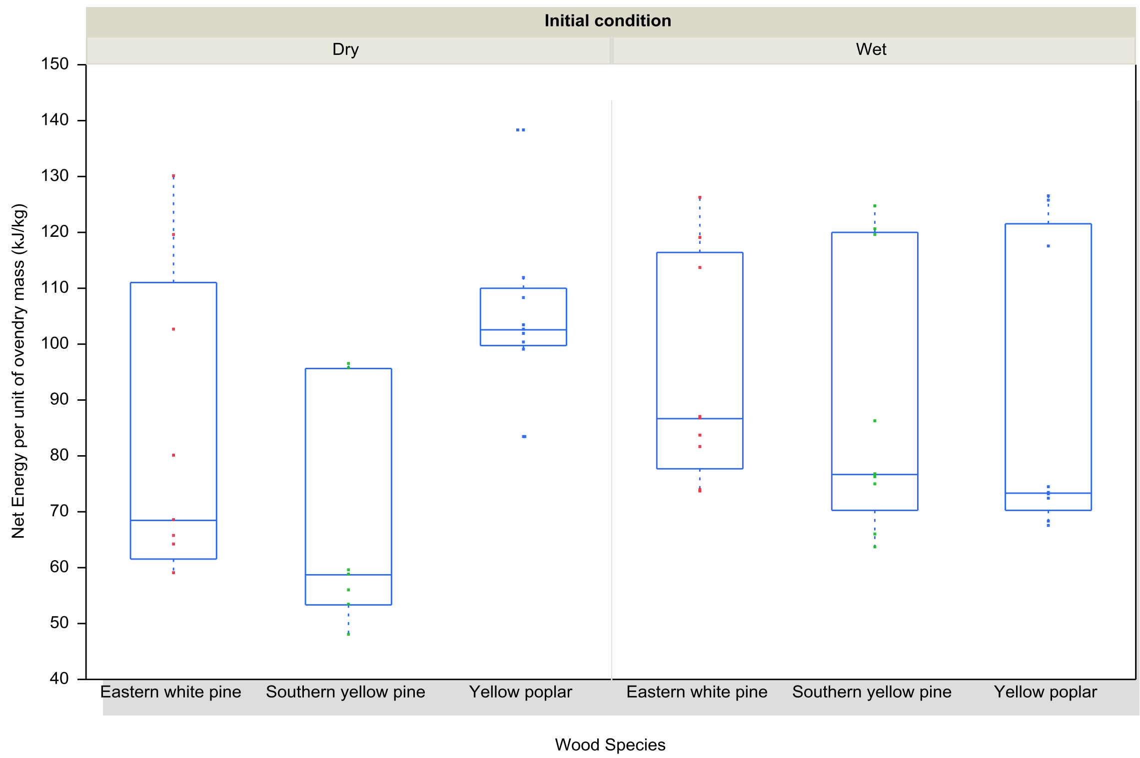


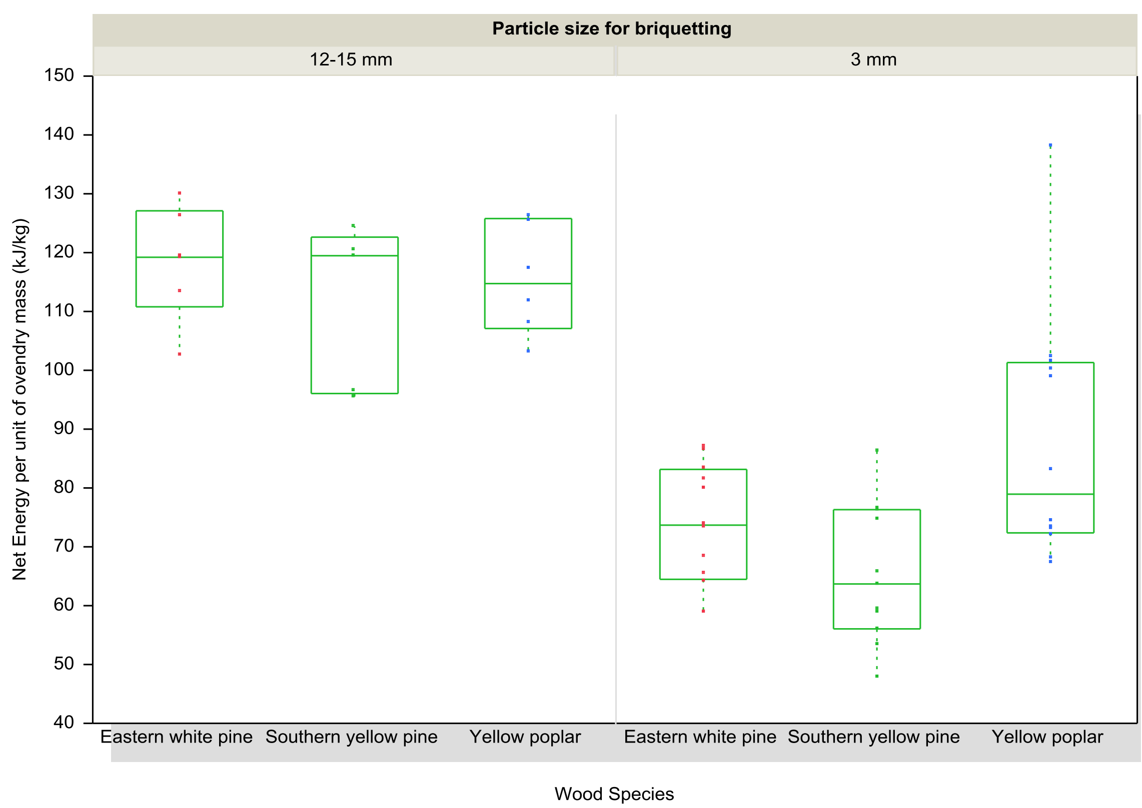
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.99223

Level				Least Sq Mean
Eastern white pine,12-15 mm	A			118.45851
Yellow poplar,12-15mm	A			115.45879
Southern yellow pine,12-15 mm	A			108.78320
Yellow poplar,3 mm		B		87.78604
Eastern white pine,3 mm			C	73.53337
Southern yellow pine,3 mm			C	64.48268

Levels not connected by same letter are significantly different.


Initial condition
Dry
Wet
Net Energy per unit of ovendry mass (kJ/kg)
150
140
130
120
110
100
90
80
70
60
50
40
Eastern white pine
Southern yellow pine
Yellow poplar
Eastern white pine
Southern yellow pine
Yellow poplar
Wood Species

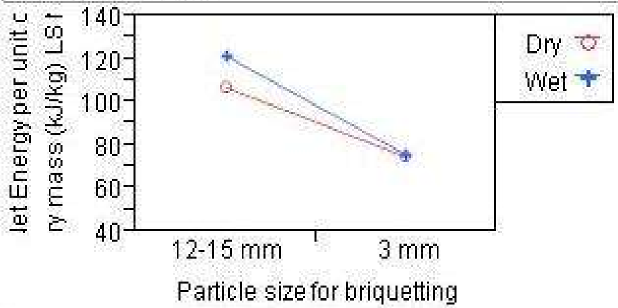

Particle size for briquetting
12-15 mm
3 mm
Net Energy per unit of ovendry mass (kJ/kg)
150
140
130
120
110
100
90
80
70
60
50
40
Eastern white pine
Southern yellow pine
Yellow poplar
Eastern white pine
Southern yellow pine
Yellow poplar
Wood Species

Initial condition*Particle size for briquetting

Least Squares Means Table

Level	Least Sq Mean	Std Error
Dry,12-15 mm	107.03204	3.1987100
Dry,3 mm	75.08454	2.1627227
Wet,12-15 mm	121.43495	2.9614300
Wet,3 mm	75.45019	2.0940472

LS Means Plot

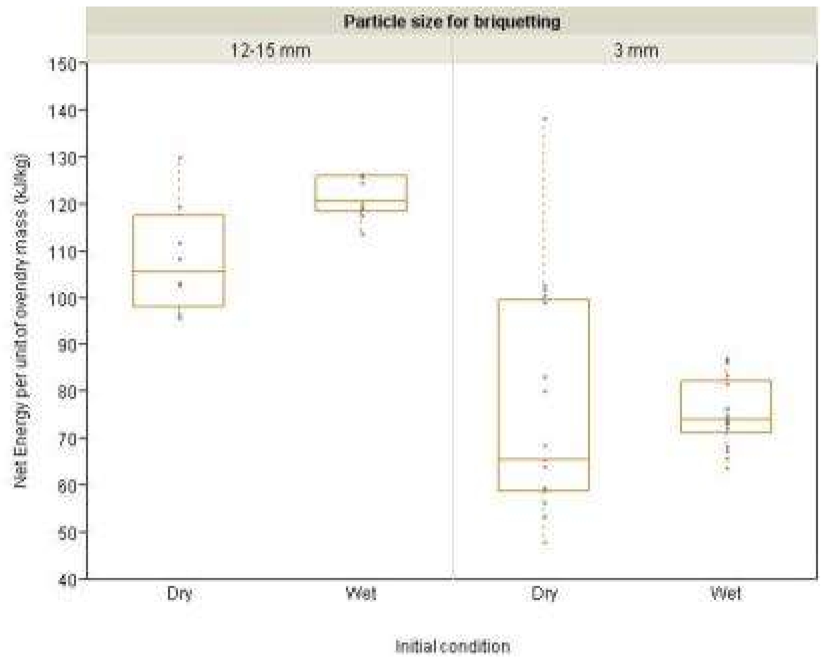


LSMeans Differences Tukey HSD

α= 0.050 Q= 2.68042

Level			Least Sq Mean
Wet,12-15 mm	A		121.43495
Dry,12-15 mm	B		107.03204
Wet,3 mm		C	75.45019
Dry,3 mm		C	75.08454

Levels not connected by same letter are significantly different.

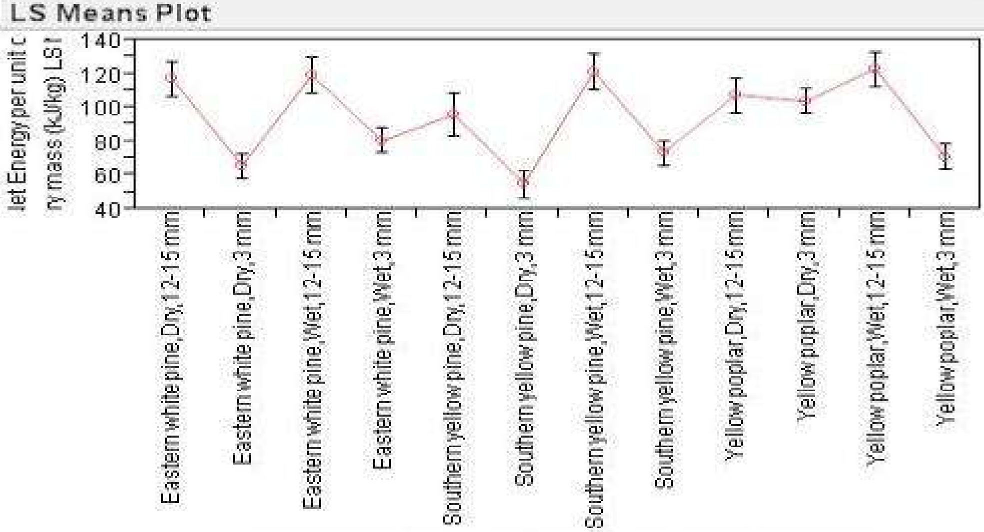


Wood Species*Initial condition*Particle size for briquetting

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,Dry,12-15 mm	117.30946	5.1293472
Eastern white pine,Dry,3 mm	66.03400	3.6269962
Eastern white pine,Wet,12-15 mm	119.60756	5.1293472
Eastern white pine,Wet,3 mm	81.03274	3.6269962
Southern yellow pine,Dry,12-15 mm	96.01040	6.2821416
Southern yellow pine,Dry,3 mm	55.07120	3.9731752
Southern yellow pine,Wet,12-15 mm	121.55600	5.1293472
Southern yellow pine,Wet,3 mm	73.89417	3.6269962
Yellow poplar,Dry,12-15 mm	107.77627	5.1293472
Yellow poplar,Dry,3 mm	104.14842	3.6269962
Yellow poplar,Wet,12-15 mm	123.14130	5.1293472
Yellow poplar,Wet,3 mm	71.42365	3.6269962

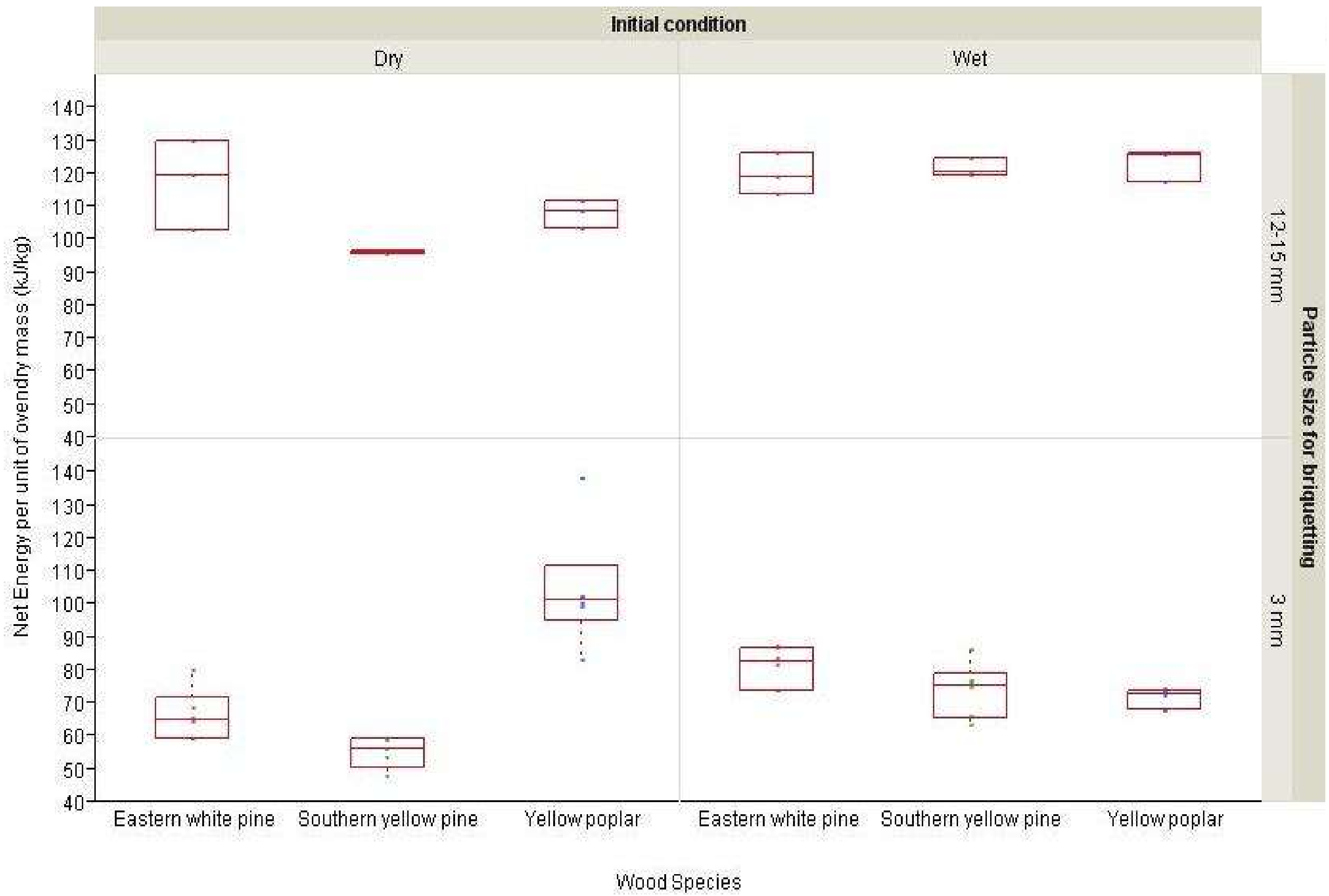
LS Means Plot



LSMeans Differences Tukey HSD

α= 0.050 Q= 3.46761

Level					Least Sq Mean
Yellow poplar,Wet,12-15 mm	A				123.14130
Southern yellow pine,Wet,12-15 mm	A				121.55600
Eastern white pine,Wet,12-15 mm	A				119.60756
Eastern white pine,Dry,12-15 mm	A				117.30946
Yellow poplar,Dry,12-15 mm	A				107.77627
Yellow poplar,Dry,3 mm	A				104.14842
Southern yellow pine,Dry,12-15 mm	A	B			96.01040
Eastern white pine,Wet,3 mm		B	C		81.03274
Southern yellow pine,Wet,3 mm		B	C		73.89417
Yellow poplar,Wet,3 mm		B	C	D	71.42365
Eastern white pine,Dry,3 mm			C	D	66.03400
Southern yellow pine,Dry,3 mm				D	55.07120



Initial condition
Dry
Wet
Particle size for briquetting
12-15 mm
3 mm
Net Energy per unit of ovendry mass (kJ/kg)
140
130
120
110
100
90
80
70
60
50
40
Eastern white pine
Southern yellow pine
Yellow poplar
Wood Species

Table A 7: JMP output of the full factorial ANOVA with interactions for energy density of wood briquettes

Whole Model

Summary of Fit

RSquare	0.67874
RSquare Adj	0.655181
Root Mean Square Error	0.667789
Mean of Response	13.53029
Observations (or Sum Wgts)	162

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	141.32406	12.8476	28.8101
Error	150	66.89131	0.4459	**Prob > F**
C. Total	161	208.21538		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	13.426695	0.055649	241.27	<.0001*
Wood species[Eastern white pine]	0.9750617	0.0787	12.39	<.0001*
Wood species[Southern yellow pine]	-0.119734	0.0787	-1.52	0.1303
Initial condition of raw material[dry]	-0.171101	0.055649	-3.07	0.0025*
Wood species[Eastern white pine]*Initial condition of raw material[dry]	-0.16999	0.0787	-2.16	0.0324*
Wood species[Southern yellow pine]*Initial condition of raw material[dry]	-0.365514	0.0787	-4.64	<.0001*
Particle size for densification (mm)[12-15]	-0.310794	0.055649	-5.58	<.0001*
Wood species[Eastern white pine]*Particle size for densification (mm)[12-15]	-0.024504	0.0787	-0.31	0.7560
Wood species[Southern yellow pine]*Particle size for densification (mm)[12-15]	-0.017551	0.0787	-0.22	0.8238
Initial condition of raw material[dry]*Particle size for densification (mm)[12-15]	-0.169957	0.055649	-3.05	0.0027*
Wood species[Eastern white pine]*Initial condition of raw material[dry]*Particle size for densification (mm)[12-15]	0.2043108	0.0787	2.60	0.0104*
Wood species[Southern yellow pine]*Initial condition of raw material[dry]*Particle size for densification (mm)[12-15]	-0.296193	0.0787	-3.76	0.0002*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Wood species	2	2	81.440045	91.3124	<.0001*
Initial condition of raw material	1	1	4.215698	9.4535	0.0025*
Wood species*Initial condition of raw material	2	2	21.564572	24.1787	<.0001*
Particle size for densification (mm)	1	1	13.909422	31.1911	<.0001*
Wood species*Particle size for densification (mm)	2	2	0.128499	0.1441	0.8659
Initial condition of raw material*Particle size for densification (mm)	1	1	4.159513	9.3275	0.0027*
Wood species*Initial condition of raw material*Particle size for densification (mm)	2	2	6.619963	7.4224	0.0008*

Wood species

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Eastern white pine	14.401757	0.09638703	14.5135
Southern yellow pine	13.306961	0.09638703	13.4164
Yellow poplar	12.571367	0.09638703	12.6609

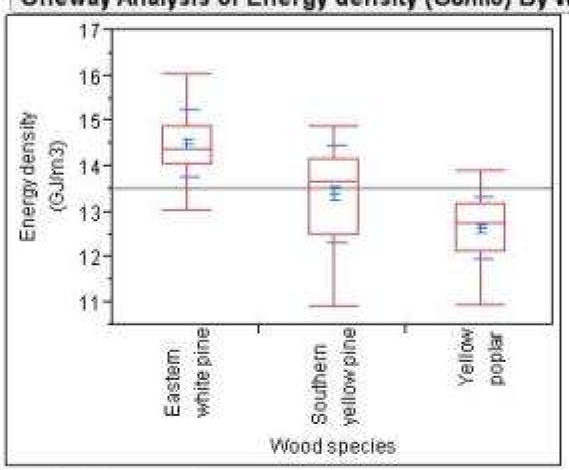
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.36725

Level				Least Sq Mean
Eastern white pine	A			14.401757
Southern yellow pine		B		13.306961
Yellow poplar			C	12.571367

Levels not connected by same letter are significantly different.

Oneway Analysis of Energy density (GJ/m3) By Wood species



Missing Rows 2

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Eastern white pine	54	14.5135	0.74262	0.10106	14.311	14.716
Southern yellow pine	54	13.4164	1.05954	0.14418	13.127	13.706
Yellow poplar	54	12.6609	0.69732	0.09489	12.471	12.851

Initial condition of raw material

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
dry	13.255594	0.07869968	13.4158
wet	13.597796	0.07869968	13.6447

LSMeans Differences Student's t

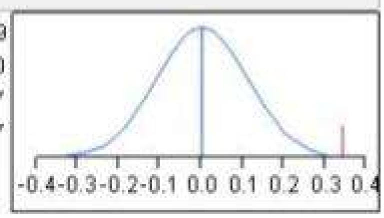
α= 0.050 t= 1.97591

Level			Least Sq Mean
wet	A		13.597796
dry		B	13.255594

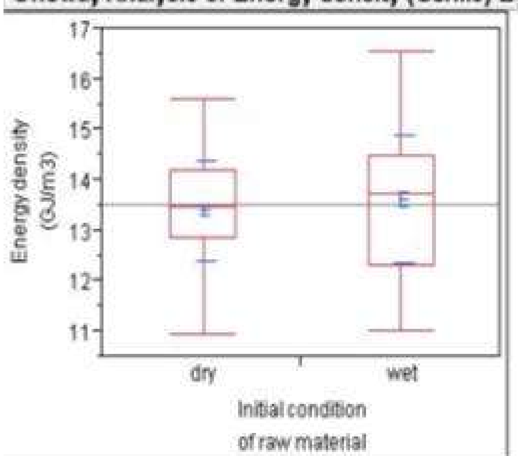
Levels not connected by same letter are significantly different.

Comparing wet with dry

Difference	0.342203	t Ratio	3.074649
Std Err Dif	0.111298	DF	150
Upper CL Dif	0.562117	Prob > |t|	0.0025*
Lower CL Dif	0.122288	Prob > t	0.0013*
Confidence	0.95	Prob < t	0.9987



Oneway Analysis of Energy density (GJ/m3) By Initial condition of raw material



Missing Rows 2

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
dry	81	13.4158	0.99851	0.11095	13.195	13.637
wet	81	13.6447	1.25664	0.13963	13.367	13.923

Particle size for densification (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
12-15	13.115900	0.09087457	13.1159
3	13.737489	0.06425802	13.7375

LSMeans Differences Student's t

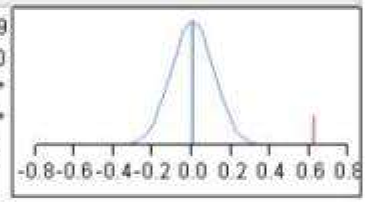
α=0.050 t= 1.97591

Level		Least Sq Mean
3	A	13.737489
12-15	B	13.115900

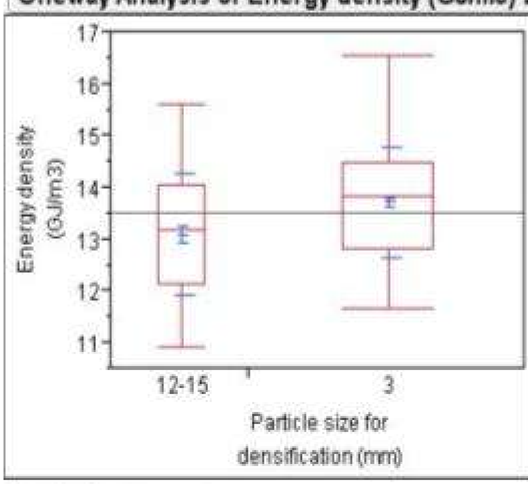
Levels not connected by same letter are significantly different.

Comparing 3 with 12-15

Difference	0.621589	t Ratio	5.584899
Std Err Dif	0.111298	DF	150
Upper CL Dif	0.841504	Prob > |t|	<.0001*
Lower CL Dif	0.401674	Prob > t	<.0001*
Confidence	0.95	Prob < t	1.0000



Oneway Analysis of Energy density (GJ/m3) By Particle size for densification (mm)



Missing Rows 2

Means and Std Deviations

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
12-15	54	13.1159	1.17020	0.15924	12.796	13.435
3	108	13.7375	1.06661	0.10263	13.534	13.941

Wood species*Initial condition of raw material

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,dry	14.060665	0.13631185
Eastern white pine,wet	14.742848	0.13631185
Southern yellow pine,dry	12.770346	0.13631185
Southern yellow pine,wet	13.843577	0.13631185
Yellow poplar,dry	12.935770	0.13631185
Yellow poplar,wet	12.206964	0.13631185

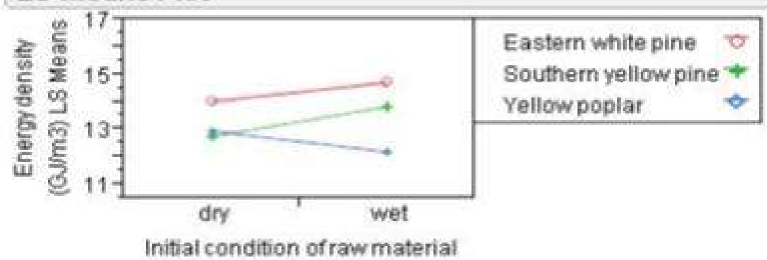
LSMeans Differences Tukey HSD

α= 0.050 Q= 2.88691

Level					Least Sq Mean
Eastern white pine,wet	A				14.742848
Eastern white pine,dry		B			14.060665
Southern yellow pine,wet		B			13.843577
Yellow poplar,dry			C		12.935770
Southern yellow pine,dry			C		12.770346
Yellow poplar,wet				D	12.206964

Levels not connected by same letter are significantly different.

LS Means Plot



Initial condition of raw material*Particle size for densification (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error
dry,12-15	12.774842	0.12851605
dry,3	13.736345	0.09087457
wet,12-15	13.456959	0.12851605
wet,3	13.738633	0.09087457

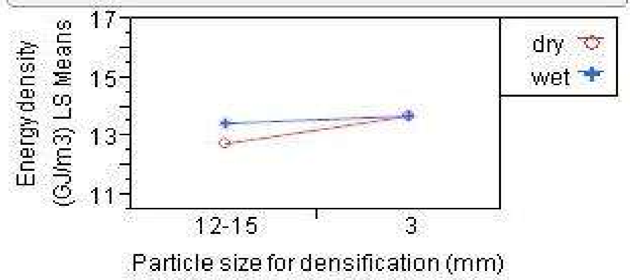
LSMeans Differences Tukey HSD

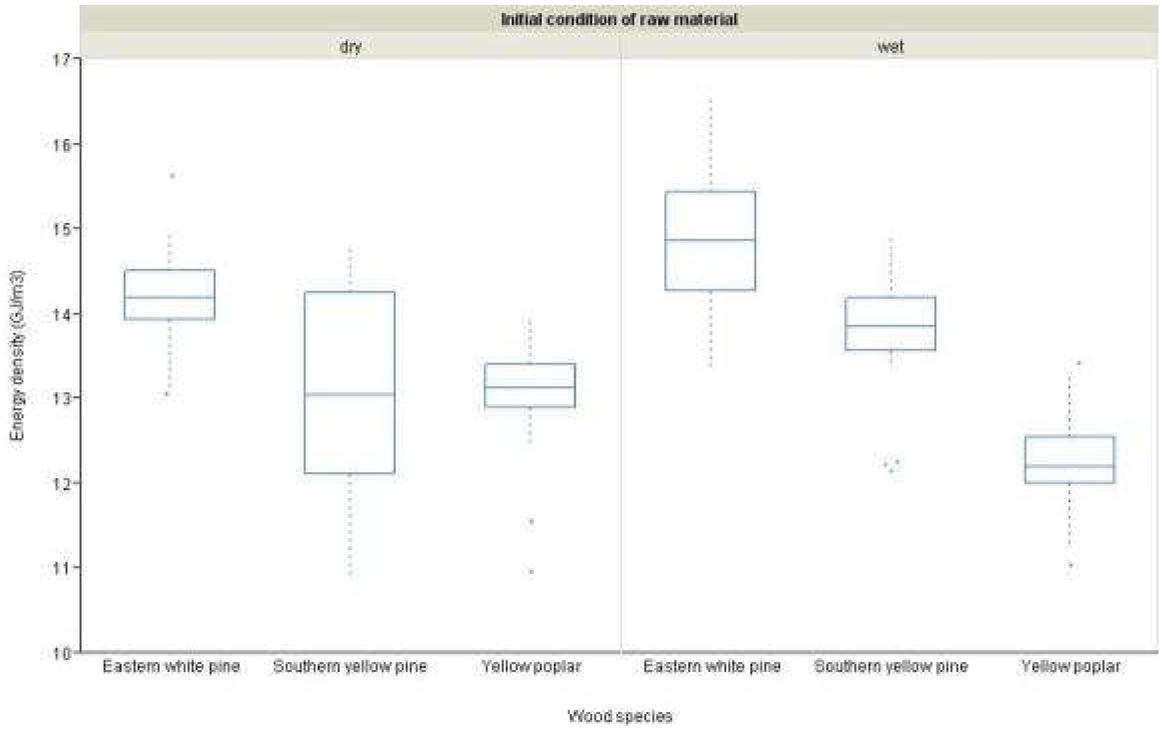
α= 0.050 Q= 2.59807

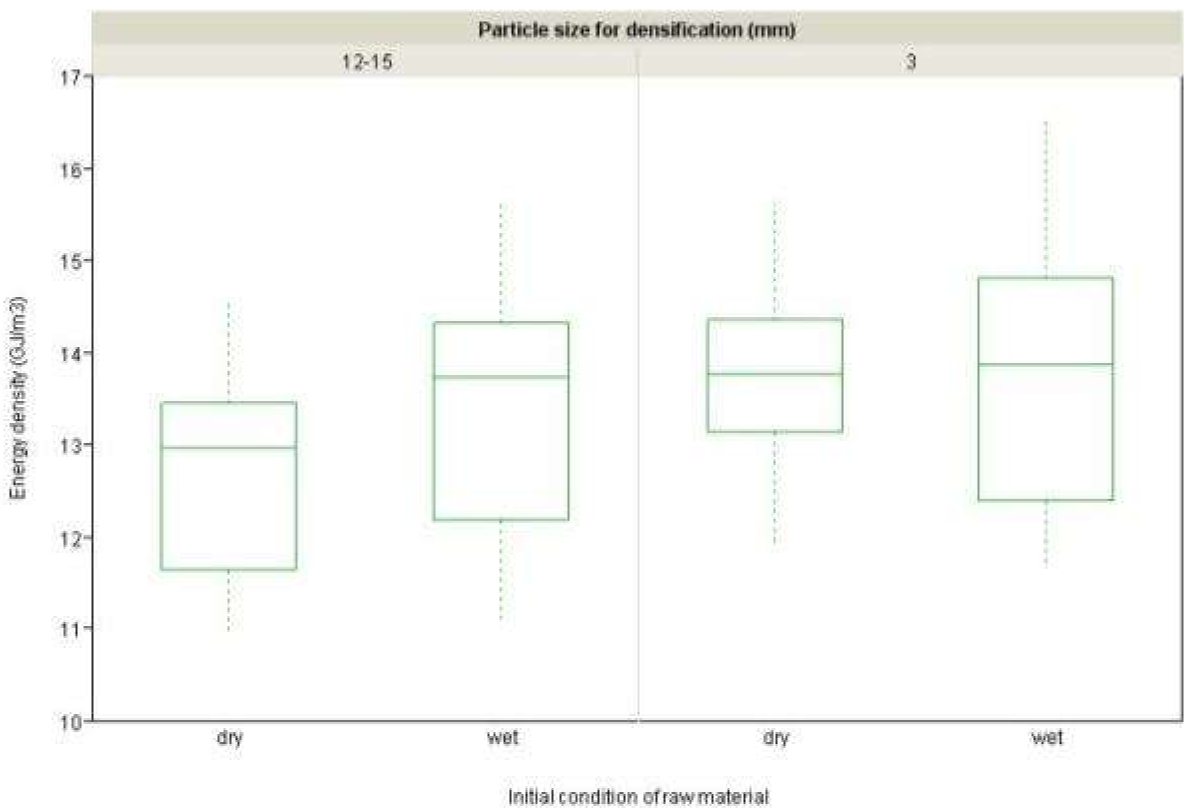
Level			Least Sq Mean
wet,3	A		13.738633
dry,3	A		13.736345
wet,12-15	A		13.456959
dry,12-15		B	12.774842

Levels not connected by same letter are significantly different

LS Means Plot




Initial condition of raw material
dry
wet
Energy density (GJ/m3)
17
16
15
14
13
12
11
10
Eastern white pine
Southern yellow pine
Yellow poplar
Eastern white pine
Southern yellow pine
Yellow poplar
Wood species


Particle size for densification (mm)
12-15
3
Energy density (GJ/m3)
17
16
15
14
13
12
11
10
dry
wet
dry
wet
Initial condition of raw material

Wood species*Initial condition of raw material*Particle size for densification (mm)

Least Squares Means Table

Level	Least Sq Mean	Std Error
Eastern white pine,dry,12-15	13.759720	0.22259632
Eastern white pine,dry,3	14.361610	0.15739937
Eastern white pine,wet,12-15	14.373196	0.22259632
Eastern white pine,wet,3	15.112500	0.15739937
Southern yellow pine,dry,12-15	11.975850	0.22259632
Southern yellow pine,dry,3	13.564842	0.15739937
Southern yellow pine,wet,12-15	13.981382	0.22259632
Southern yellow pine,wet,3	13.705771	0.15739937
Yellow poplar,dry,12-15	12.588955	0.22259632
Yellow poplar,dry,3	13.282584	0.15739937
Yellow poplar,wet,12-15	12.016299	0.22259632
Yellow poplar,wet,3	12.397629	0.15739937

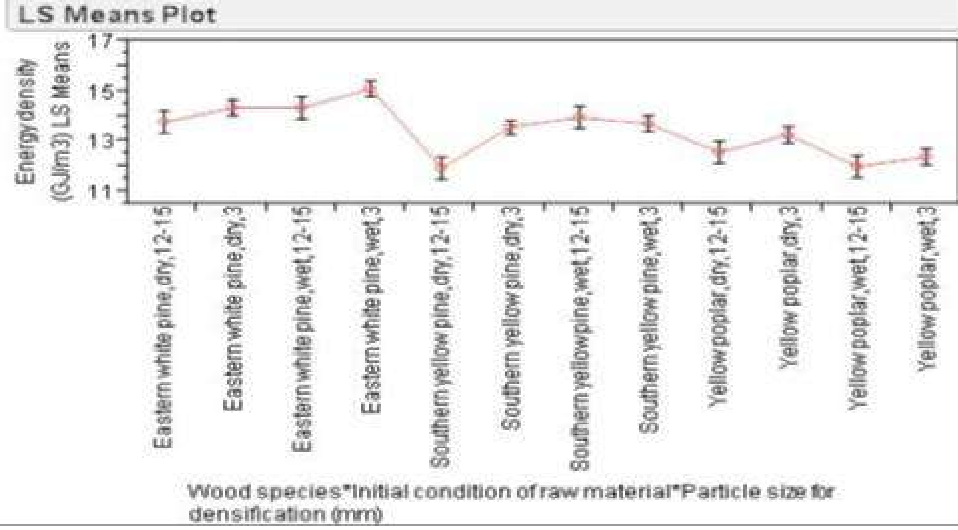
LSMeans Differences Tukey HSD

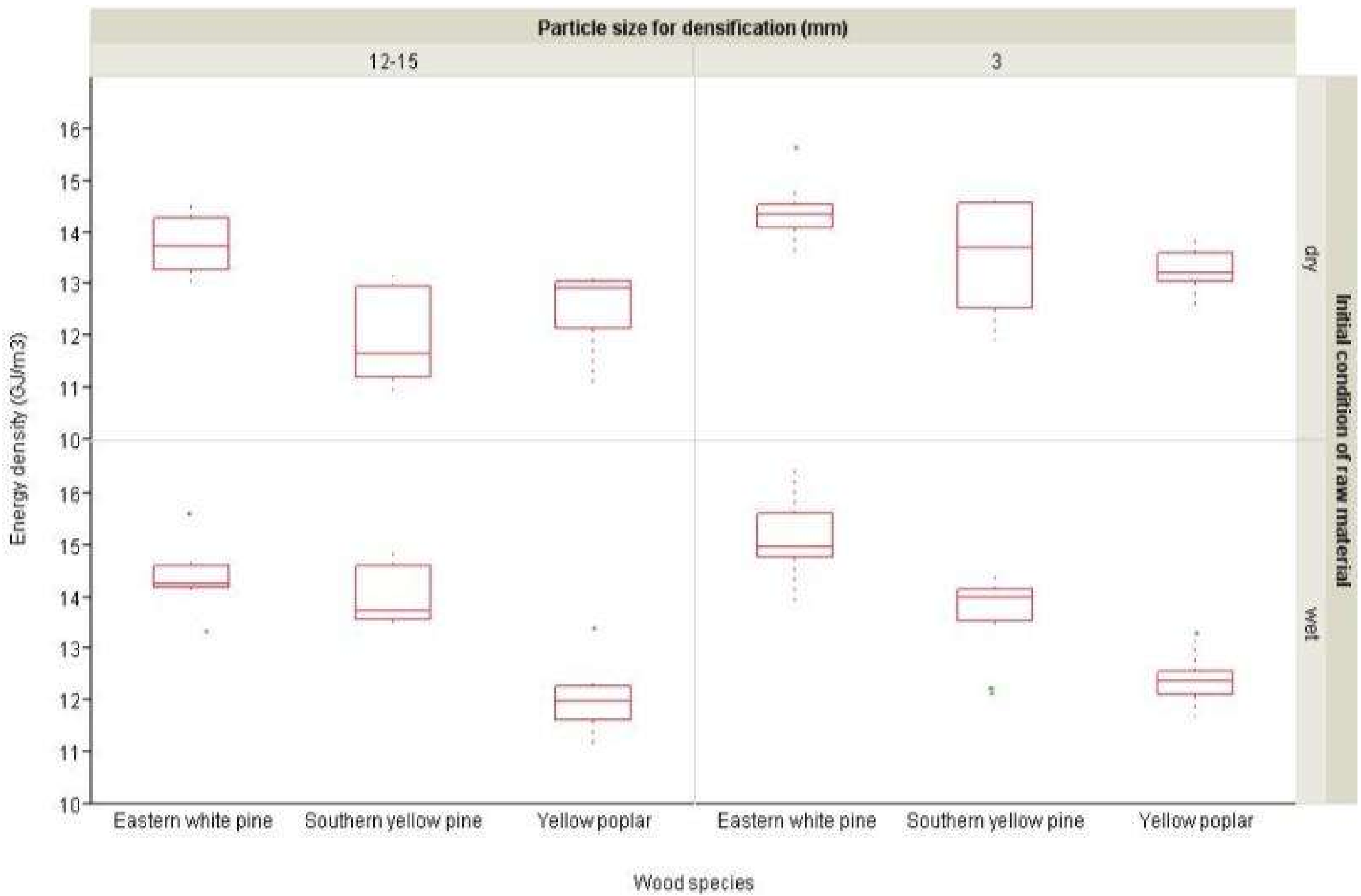
α= 0.050 Q= 3.3204

Level							Least Sq Mean
Eastern white pine,wet,3	A						15.112500
Eastern white pine,wet,12-15	A	B	C				14.373196
Eastern white pine,dry,3		B					14.361610
Southern yellow pine,wet,12-15		B	C	D			13.981382
Eastern white pine,dry,12-15		B	C	D			13.759720
Southern yellow pine,wet,3		B	C	D			13.705771
Southern yellow pine,dry,3			C	D			13.564842
Yellow poplar,dry,3				D	E		13.282584
Yellow poplar,dry,12-15					E	F	12.588955
Yellow poplar,wet,3						F	12.397629
Yellow poplar,wet,12-15						F	12.016299
Southern yellow pine,dry,12-15						F	11.975850

Levels not connected by same letter are significantly different.

LS Means Plot





Particle size for densification (mm)
12-15
3
Energy density (GJ/m3)
16
15
14
13
12
11
10
dry
wet
Initial condition of raw material
Eastern white pine
Southern yellow pine
Yellow poplar
Wood species