Energy Balance in Sawing *Eucalyptus grandis* Logs

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The potential energy balance of the sawing logs for *Eucalyptus* lumber production was determined. *Eucalyptus grandis* logs (n = 10) were sawn with a band saw, and the planks were re-sawed with a circular saw. The sawing yield was calculated with the volumes of logs, lumbers, and wastes. The consumption of electric energy was measured using a multifunctional meter. The energy stored in the wood was determined by the lower calorific value of wood; the superior calorific value was calculated and converted into the respective active energy (kWh) value. The potential energy balance was calculated using the values of the consumed electricity in the saws and that of the energy stored in the waste. Another energy balance was calculated by considering the energy stored in the timber. The potential energy balance for sawing 1 m³ of log was equal to 1,206 kWh, considering only the energy stored in the waste. When added to energy stored in the timber, the energy balance was 2,671 kWh. The positive results of energy balances demonstrate the potential of energetic self-sufficiency of timber production.

Keywords: Sawmill; kWh; Sawing; Waste; Timber; Residuals

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INTRODUCTION

The timber industries in Brazil that produce lumber have approximately 10,000 units, with a predominance of small scale facilities (SBS 2008). Of these, approximately 60% of the industry uses native hardwood trees, and the remaining facilities process planted *Pinus* and *Eucalyptus*. The main *Eucalyptus* processed in the south and southeast of Brazil are *Eucalyptus camaldulensis, E. citriodora, E. cloeziana,* and *E. grandis* (Angeli 2006).

The energy consumed in sawmills is mainly used to operate primary and secondary saws. The main saw cuts logs longitudinally, transforming them into blocks, planks, or boards. This equipment consumes a large amount of energy for operation (Williston 1976) compared with other machines at a sawmill. The band saw is also one of the main saws, which consists essentially of a continuous steel blade tensioned by two wheels, which gives good production and has a motor power of 20 to 300 hp (Rocha 2002). The secondary saws (*e.g.*, circular saw) are smaller and used for cutting logs and producing lumber in small sawmills (Gomide 1977).

The energy consumed in sawmills has different origins, such as by burning of fossil fuels, hydropower, or burning of waste, varying according to their technological level, the kind of product, and geographic location. The availability and consumption of energy in sawmills are limiting factors because they interfere with the production costs and operation of the company. The amount of energy consumed can be measured with electric meters.

Life cycle assessment (LCA) is method for evaluating the environmental impacts of products. The energy efficiency is important in LCA and shows that the production of wood-based materials is advantageous compared with other materials, such as steel, concrete, and ceramics (Ferguson *et al.* 1996). For example, the manufacturing and pre-manufacturing of wooden doors consumes a lower amount of energy than producing steel doors (Knight *et al.* 2005). Other studies that compared wood-based materials with other materials showed positive results for wood-based materials (Upton *et al*. 2008; Sathre and Gustavsson 2009).

Wood-based materials generate a large volume of waste for their production, mainly during the mechanical processing of wood. In the sawmill, the volume of waste is > 50% of the volume of the logs, as reported in several studies of *Eucalyptus* logs (Scanavaca and Garcia 2003; Ferreira *et al*. 2004; Monteiro *et al*. 2013).

The waste generated from wood burning is used for the generation of electric power, which helps prevent wastage from the burning of fossil fuels and reduces electricity costs in the industry. The generation of electricity by burning wood waste replacing fossil fuels is advantageous from an environmental point of view due to the reduced emissions of greenhouse gases (Dowaki 2005).

A large amount of waste is generated in sawmills, which has the potential to generate thermal and electrical energies. The control over energy consumption in sawmills is fundamental to the management of this industry and to the reduction of environmental impacts. Thus, this study evaluated the energy balance (EB) of the sawing of *Eucalyptus grandis* logs for lumber production.

EXPERIMENTAL

Log Characteristics

Ten *Eucalyptus grandis* trees (15-year-old) were cut into logs of length 3.5 m from the campus of Universidade Federal de Lavras (UFLA) in Lavras, Minas Gerais state, Brazil. A basal log measuring 3.5 m in length and two wood discs (100-mm thickness) were cut from the two ends of the log of each tree for the determination of the basic density and moisture. Two opposite wedges (defect-free) were obtained from the discs. The average value of the wedges was used to determine the basic density of wood according to the Brazilian standard NBR 11941 (2003) and the moisture content according to the NBR 7190 (1997) for each log.

Lumber Production

The methods of sawing and the selection of the equipment were the same as suggested by Monteiro *et al.* (2013). The logs were cut with a vertical simple band saw, with the wheel of 1,000 mm diameter and a 40 hp engine. The logs were transported in a log carriage with a 7.5 hp engine capable of carrying logs about 4 m in length. The sawing was developed with six successive cuts in each log. The lumber was obtained with re-sawing in a circular saw having 48 teeth and a 10 hp engine. Eleven cuts were made randomly in the four planks of each log.

The lumber was produced according to the dimensions recommended by the NBR 7190 (1997). In this standard, the main parts had a minimum area of cross-section of 5,000 mm² and a minimum thickness of 50 mm, while the limits for the secondary parts were reduced to 1,800 mm² and 18 mm, respectively.

Rating of Mechanical Processing

The volume of logs was measured. The volume of planks and lumber was obtained by multiplying their cross-section area and length. The volume of sawdust was determined by multiplying the thickness, length, and height of the cuts for band and circular saw. The slabwood volume was obtained with the difference between the volume of the logs and the volume of planks and sawdust. The volume of edgings was obtained from the difference between the volume of the planks and the volume of lumber and sawdust. The volume of bark was obtained by calculating the difference between the volume of logs with bark and the volume of logs without bark (calculated disregarding the thickness of the bark). The yield (%) of lumber and the percentage of the different wastes were also calculated.

Energy Consumed in the Sawing of Logs

The electric energy consumed in the sawing of logs occurred in two stages. The first phase included a log cut in the band saw and the round trip of the carriage. The second phase included there-sawing of the planks in the circular saw and the intervals between the cuts.

The energy consumed was measured using a device to measure the multifunctional power. The collected data were transferred to a computer and analyzed in a spreadsheet. The energy consumption was obtained for each log, considering the cuts in the band saw and circular saw separately. The active energy (kWh) was used for the calculations and estimated for sawing 1 m³ of logs and to produce 1 m³ of lumber.

Energy Stored in the Wood Waste and Lumber

The energy stored in the lumber and in the wastes such as slabwood, edgings, sawdust, and bark was first calculated using the superior calorific value (SCV). In the Biomaterials Laboratory at UFLA, the SCV was determined according to the Brazilian standard NBR 8633 (1984) in the calorimetric bomb digital *IKA C-200*. Then, the lower calorific value (LCV), which considered the moisture content of the wood, was calculated (Eq. 1), according to Protásio *et al*. (2013),

$$LCV = SCV - 5.72 \, x \, ((9*H) + M) \tag{1}$$

where H is the hydrogen content (%) obtained in the elemental chemical analysis and M is the moisture content (%).

LCV and SCV present the unity in calories (cal). The results (in kcal) were converted to kilowatt-hours (kWh) using the 1st principle of thermodynamics, where 1 kWh is equivalent to 859.85 kcal for standardization of units. The conversion of units (kWh for kcal) ignores the losses in the transformation of biomass energy into electrical energy, as in boilers.

Energy Balance

The potential EB was calculated in two ways: (i) by considering the potential EB as the difference between the energy stored in the waste of sawing and active energy consumed in the saws (Eq. 2) and (ii) by using the second EB (Eq. 3) that added the energy stored in the lumber by simulating the discard after use, as performed in the life cycle analysis (LCA) of the products,

$$EB = (A_b + A_s + A_{sl} + A_e) - (A_{bs} + A_{cs}) \quad (2)$$

$$EB_l = (A_b + A_s + A_{sl} + A_e + A_l) - (A_{bs} + A_{cs}) \quad (3)$$

where EB is the energy balance (kWh); EB_l is the energy balance with the energy stored in waste and lumber (kWh); A_b is the energy stored in the bark (kWh); A_s is the energy stored in the sawdust (kWh); A_{sl} is the energy stored in the slabwood (kWh); A_e is the energy stored in the edgings (kWh); A_l is the energy stored in the lumber (kWh); A_{bs} is the energy consumed in the bandsaw (kWh); and A_{cs} is the energy consumed in the circular saw (kWh).

The parameters used in the potential energy balance of the log sawing were the average energy consumed in the cutting of each log, the average energy stored in the waste, and the average energy stored in the lumber. The standard deviation and coefficient of variation were calculated.

The parameters for the assessment of the properties of logs, lumber yield, percentage of waste, and the energy consumed in the saws was the average value and the coefficient of variation. The evaluation of the energy stored in the different waste used a completely randomized design with three treatments (slabwood more edgings, sawdust, and bark) and ten repetitions. Tukey's test at 5% significance level was used for multiple comparisons.

RESULTS AND DISCUSSION

The mean log diameter (Table 1) was consistent with reported values for similar trees, *e.g.*, 13-year-old *Eucalyptus* logs in classes of 0.25 m and 0.30 m diameter (Rocha and Trugilho 2006). The diameter class used in this study provided satisfactory yield compared with smaller diameter logs. For example, Borges *et al.* (1993) compared the yield of lumber for different diameter classes, finding the highest yields in the diameter class of 0.30 m. The homogeneity in the diameter of the logs used here (Table 1, CV = 13.57%) can produce a better use of the log during the production of the lumbers.

Table 1. Descriptive Statistics of Log Characteristics and Proportion of Products and Waste after Sawing

Log characteristic	Mean		Minimum	Maximum	# of observations
Diameter (m)	0.34	[13.57]	0.29	0.42	
Basic density (kg.m^{-3})	499	[15.24]	413.2	558.0	10
Moisture (%)	30.78	[9.43]	23.19	40.49	
Products and waste proportion					
Lumber yield (%)	43.8	[14.24]	31	54.7	
Bark (%)	9.9	[25.61]	6.5	15.8	
Sawdust (%)	9.3	[13.75]	7	10.9	10
Slabwood (%)	24.8	[19.62]	15.7	30.9	
Edgings (%)	12.2	[28.16]	4.6	17.1	

[ ] coefficient of variation (%)

The mean basic density of the logs (Table 1) was lower than reported values for *Eucalyptus* of the same age. The basic density of wood ranged from 566 to 575 kg/m³ in

13-year-old *E. grandis* (Rezende and Ferraz 1985) and from 447 to 552 kg/m³ in 6-year-old *E. grandis* x *E. urophylla* hybrids (Queiroz *et al.* 2004). The lower wood density of these trees (Table 1) can be explained by their growing conditions. The trees had no defined spacing, and the plantation of the seedlings was performed using seeds. The literature reports studies using homogeneous stands of trees, including mainly those obtained from seedling clones.

The mean moisture content (MC) was slightly below the desirable value for log sawing. After harvesting the logs, their wood presented with an optimum moisture content for the mechanical processing operations. Here, the moisture content near the saturation point of the fibers (MC = approximately 31%; Table 1) occurred due to the long duration for which the logs were stored in the sawmill courtyard. The homogeneity of the logs MC (CV = 15.2%) may partly be explained by the homogeneity of the diameter of logs (CV = 13.6%), which is directly related to drying (Rezende *et al.* 2011).

The analysis of lumber yield and waste proportions revealed that most of the volume of the log results in waste generation (Table 1). The yield of lumber was composed by primary structural parts (20.9%) and secondary structural parts (22.9%), which agree with the reported values in the literature, such as an average yield of 42.5% for the sawing of 19-year-old *Eucalyptus urophylla* logs (Scanavaca and Garcia 2003). The yield of < 50% was obtained for hardwood species, which is common in the literature because of factors such as the quality of raw material, the method of sawing, equipment, and qualification of manpower used in log sawing.

The waste generated represented 56.2% of the log volume. The slabwood and edgings were the residues with the highest percentages (Table 1). The percentages of these wastes were higher than those found by Vital (2008), who reported a yield of 14.29% for slabwood and 6.18% for edgings in the same diameter class. The differences between these results can be explained by the standardization of the number of cuts in each log in order to better assess the energy consumption, which is the main aim of the present investigation. Compared with the same database (Vital 2008), this study showed that the lowest percentage of slabwood and edgings resulted in a higher percentage of sawdust due to cuts in slabwood and edgings for production of small parts.

The percentage of bark (Table 1) is consistent with previously reported values. The bark percentage in *Eucalyptus grandis* varied from 7.9% to11.8%, and the value declined with increasing diameter of the logs (Vital *et al.* 1989). The percentage reached 14.4% for 7-year-old *E. grandis* from the first rotation plantations (Seixas *et al.* 2005).

Table 2 shows the active energy (kWh) consumed in the band saw for the sawing of the logs and in the circular saw to re-saw planks and the average energy stored in the lumber and waste of one log.

The sawing operation of logs of approximately 0.3 m³ using a band and circular saw consumed an active energy of 26.79 kWh. Each sawing process produced 0.133 m³ (average) of lumber per log. The highest energy consumption was by the bandsaw (18.30 kWh), in part due to the high potency of its engine (40 hp) compared with the circular saw engine (10 hp). Other factors also interfered in this process, such as the lower heights of cuts in the boards. The circular saw gave the greatest coefficient of variation in the consumption of active energy (kWh) compared with the band saw (Table 2). One hypothesis for the greater variation in the circular saw was the low engine power (10 hp), a fact that reflects on how the workman performs its work. For example, the different speed feed rates that apply in each cut and pick-up the variations of the wood properties in each cut better, such as the radial variations of physical and mechanical properties of wood.

Table 2. Descriptive Statistics of Active Energy (kWh) Consumed by the Band and Circular Saw and Total Energy Consumed by Two Saws for the Lumber Production

Active Energy Consumed			
	Mean (kWh)	Volume (m³)	# of observations
Band saw	18.3 [4.95]	0.300 [27.68]	10
Circular saw	8.5 [14.0]	0.180 [30.74]	
Log sawing	26.8 [7.20]	0.300 [27.68]	10
	89.33	1	Stimed
Lumber produced	26.8 [7.20]	0.133 [35.56]	10
	201.50	1	Stimed
Active energy stored			
	Mean (kWh)	Volume (m³)	# of observations
Edgings	88.72 [35.19]	0.036 [34.91]	10
Slabwood	185.05 [32.87]	0.074 [32.03]	
Sawdust	67.15 [16.65]	0.027 [13.87]	
Bark	47.68 [36.41]	0.030 [35.41]	
Waste total	388.6 [2.18]	0.167 [25.12]	10
	2326.95	1	Stimed
Lumber	439.03 [0.70]	0.133 [35.56]	10
	3300.98	1	Stimed

[ ] coefficient of variation (%)

The variation in the active energy consumption during the sawing of logs in the band saw and during re-sawing of the boards in the circular saw is presented in Fig. 1. The interval between the sawing of one log and another and the interval between re-sawing of the planks of each log are also presented in Fig. 1.

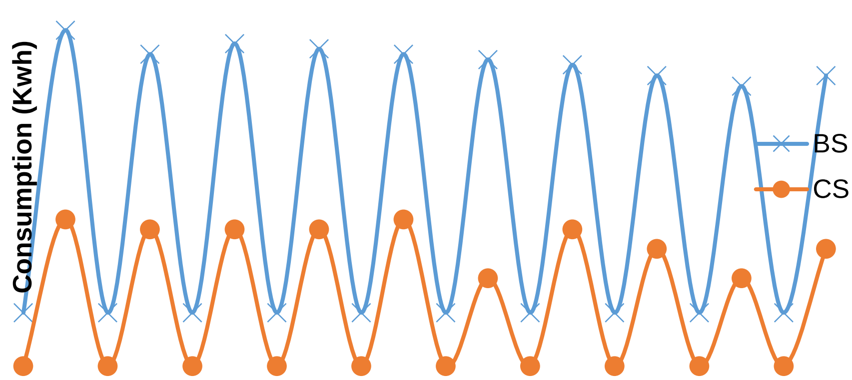

Fig. 1. Active energy consumed in the band saw (BS) and circular saw (CS) for each log

The active energy consumed in the band saw was 4.61 kWh, considering the times when the saw was not in operation and the active energy consumed in the circular saw was equal to 1.73 kWh under the same condition. The active energy consumed at the moment of the cuts in the band and circular saw were, respectively, 3.97- and 4.90-times greater than the energy consumed in the intervals between the cuts of the saws.

The variation in the active energy consumed by the band saw during the cuts of logs was lower than the variation of energy consumed by the circular saw for the cuts in the planks. The high-power engine (40 hp) of the band saw reflected fewer changes in the dimensional properties (diameter) and physical properties (density and moisture) of the logs. However, the circular saw with an engine of 10 hp better reflected the variations in the properties of the planks.

The energy consumption required to produce 1 m³ of lumber (Table 2) in this study was consistent with values reported elsewhere. The consumption of 111.26 kWh and 1.43 t.vaporh m^{-3} of dried pine lumber gave a yield of 38.62% in one study (Brand *et al*. 2002), while the consumption of 247 kWh and 3.17 t.vaporh m^{-3} produced 1 m³ of dry pine lumber with a yield of 35% in another study (Kock 1976). The difference between active power consumption for the production of pine lumber is due to the different efficiency levels of equipment used in the production process (Brand *et al.* 2002).

The energy consumed in the sawmill should be compared, taking into account factors such as the quality and accuracy of energy consumption meter and the model of saw (band or circular saw) used in the cuts that affect the amount of energy consumed in the industry. The dimensions of the log also interfered in the power consumption due to a change in the number and length of the cuts and the extended duration of the production process of lumber from logs with high volume. The planks of the logs 6 and 9 consumed less energy in the cuts in the circular saw when compared to the other logs (Fig. 1). The smaller thickness of these planks, as well as the beginning of cracks in these pieces may have contributed to this result.

The energy stored in the lumber was higher despite the lower amount of volume (Table 2) because of the variation in the energy content of the various wastes. The average superior caloric value (SCV) of wood, excluding the bark, was 4,730 kcal/kg^1. This value is close to that reported for the bole of *E. grandis* that has an SCV of 4,641 kcal/kg^1 (Vale *et al*. 2000).

Table 2 presents the estimated values of the energy stored in 1 m³ of each type of waste (slabwood, edgings, sawdust, and bark) generated in the log sawing. The energy stored in the slabwood and edgings was high due to the higher volume and SCV of the waste. The bark presented a higher volume and lower amount of stored energy than sawdust, due in part to the low SCV of the bark (3,845 kcal/kg^1) compared with that of the sawdust (4,715 kcal/kg^1).

Analysis of variance revealed a statistically significant difference (5% of the significance level) between the wastes and also showed a low coefficient of experimental variation (9.56%). Figure 2 compares the mean values of SCV in the edgings and slabwood from the sawdust and from the bark of *E. grandis*.

The hypothesis for explaining the lower amount of energy stored in the bark is based on its chemical and physical differences from other wood wastes. The sawdust, edgings, and slabwood were removed from the log at the same radial position, which justifies the significant difference between the energy stored within such residues.

Table 3 presents the estimated values for the energy balance of the sawing of 1 m³ logs (estimated with an increasing amount and equal dimensions of the logs) and the values for the production of 1 m³ of lumber. These values take into consideration EB of the energy consumed by the saws and the energy stored in waste, as well as the second energy balance

(EBt) that adds to the energy stored in lumber. The difference between the balance of the sawing of logs and lumber production can be attributed to the amount of waste generated; for example, 1.25 m³ of waste is generated in the production of 1 m³ of lumber.

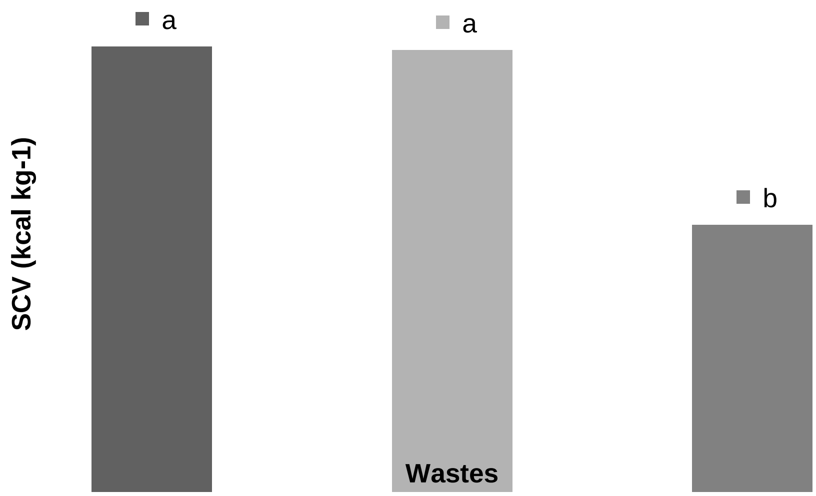

Fig. 2. Comparison of the superior calorific value in the different residues. The means followed by the same letter do not differ statistically at 5% significance by the Tukey's test.

Table 3. Average Energy Balance of Log Sawing and Average Values of the Energy Balances for the Sawing of 1 m³ of Logs to Produce 1 m³ of Lumber

		Log Sawing		Lumber Produced	
EB	Volume analyzed (m³)	0.300	1	0.133	1
	Energy balance (kWh)	361.80 [26.59]	1206.92	361.80 [26.59]	2718.47
	N	10	Stimed	10	Stimed
Ebt	Volume analyzed (m³)	0.300	1	0.133	1
	Energy balance (kWh)	800.83 [27.54]	2669.43	800.83 [27.54]	6021.28
	N	10	Stimed	10	Stimed
EB: energy balance; EBt: energy balance adding the energy stored in lumber; [ ] coefficient of variation (%).					

The analysis of the two energy balances indicates that the sawing of the logs has the potential to be energy self-sufficient. The EB from the sawing of one log had a potential for sawing 10 logs in this study, which altogether consumed 267.9 kWh of power. EB and EBt disregard the losses that occur with the transformation of biomass energy into electrical energy. In a study that evaluated the stored energy as the energy generated by burning waste in a boiler, the EB was positive for the sawing of *Pinus* log, with a high volume of waste interference in this balance (Brand *et al*. 2002).

The superior result of EBt in relation to that of EB is important for the comparison of wood and other materials (*e.g.*, steel, concrete, aluminum) based on the LCA, which considers the potential energy generated by the waste material.

In this study, EB in lumber production increased by 2.2-fold, which further increased the potential for log sawing, making it energy self-sufficient. Studies of LCA with wood-based materials detected a positive energy balance in the wood, due to the energy stored in the lumber and waste (Gustavsson and Sathre 2006; Macfarlane 2009).

CONCLUSIONS

1. The amount of active energy consumed varied with the power of the saw motor.
2. The slabwood, edgings, and sawdust contained the same amount of energy per unit volume.
3. The EB that considers the energy stored in waste had a potential balance of 1210 kWh/m^3 of log. For the conversion of waste energy into electrical energy, the losses in the conversion need to be ignored; the result of the EB of the log sawing had the potential energy to saw 10 logs in the experiment.
4. The EB that also considers the lumber energy stored was increased 2.2-fold compared with the balance that considers only the energy from waste.
5. The positive results for both the EBs suggested great potential in terms of self-sufficiency in electric energy generation in the sawmill production of *E. grandis* lumber.

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