Chapter

Methodology for the Evaluation of the Electrical Energy Potential of Residual Biomass from the Wood Industry: A Case Study in Brazil

Augusto César de Mendonça Brasil

Abstract

This chapter presents in a consolidated manner the step-by-step methodology to estimate the electrical energy potential of industrial wood residues considering the dependency of the efficiency of the power plants with their size. A function of the overall efficiency with power was obtained from a best curve fit of real data both taken from the literature and from Brazilian biomass-fired power plants. The methodology was applied to the determination of the electrical energy potential of wood industry residues in the State of Pará (data collected in 2004). Two cases were analyzed: one where a constant electrical efficiency of 25% was considered (independently of the amount of residues generated) and another where the proposed function of efficiency with power was used. Results show that in the State of Pará, the existent 675 sawmills generated 2.95×10^6 t in dry basis. When the dependency of efficiency with plant size is not considered, the electrical energy potential and average installed power (3140.4 GWh and 2 MW_e) are overestimated in comparison to the herein proposed methodology (1868.8 GWh and 1 MW_e). The present methodology, considering the efficiency as a function of the power, results in an average efficiency of 12.3% (lower than 25%).

Keywords: energy potential methodology, woody biomass, biomass residues, bioelectricity, electrical overall efficiency

1. Introduction

A large amount of the Brazilian timber production is concentrated in the northern region of the country, namely in the Amazon region. This can be observed in **Figure 1**, which shows the timber production of the top five timber producer states [1]. Four out of the top five timber producer states in Brazil are within the Amazon region. These states are: Rondônia, Amazonas, Amapá, and Pará. Moreover, the State of Pará is historically the largest producer of timber in the country.

As a result of the timber production in the Amazon region, a large quantity of wood residues is generated. However, only a small amount of these residues is used as a valuable biomass energy source [2, 3]. Other industrial uses of wood residues are also minimal. In 2004, for instance, only 10% of the wood processing factories in the State of Pará used wood residues to produce plywood [4]. Usually, woody

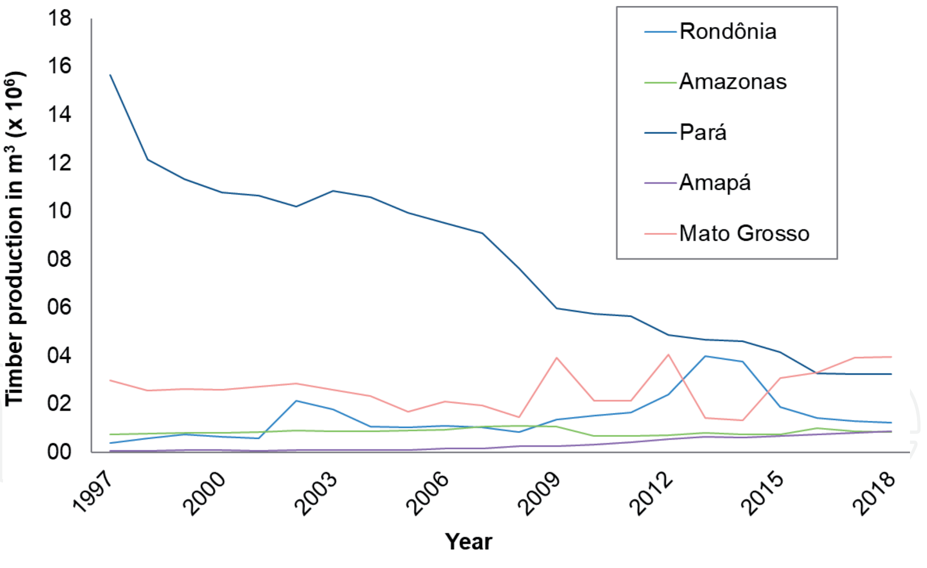

Figure 1.
Timber production of the top five timber producer states in Brazil from 1997 to 2018.

biomass residues from timber production, which are estimated to be between 58 and 62% of the log volume, become waste [5].

According to the Brazilian Energy Balance [6], in 2019, hydropower in Brazil shared 66.6% of the total 535 TWh of electric generation. At the same time, in the State of Pará, 3.0% of the electric generation is based on fossil fuels and the other 97% is hydropower generation.

The context mentioned above indicates that, in the Amazon region and, more specifically in the State of Pará, the wood residues generated by the industry are not used as an energy source, and that the electric energy resources are mainly based on one single source: hydropower. The strong dependence on hydroelectricity was also identified by da Silva et al. [7] who showed the importance of the diversification of the electricity generation mix to the energy security in Brazil.

That scenario of wood residues availability, with the possibility of using them as an energy source, and the need of diversifying the energy resources in the Amazon region, opens an opportunity for the local lumber mills to install biomass-fired power plants and also to properly valorize the residual woody biomass they generate.

In order to evaluate the viability of using wood residues as an energy resource in the State of Pará, Padilha et al. [4] estimated the electrical energy potential of the residual biomass of the wood industry in that state. The evaluation applied by Padilha et al. [4] used a constant overall efficiency for the steam turbine power plants in the determination of the biomass energy potential. The authors concluded that 70% of the lumber mills in the State of Pará could install biomass-fired power plants with a capacity between 200 and 300 kW_e.

Brasil et al. [8] revisited part of the data analyzed in 2004 by [4] and estimated an electrical energy potential of 235.5 GWh $year^{-1}$ for the wood residues from the 117 sawmills located in a region within a 100-km radius from the main hydropower plant in the State of Pará. In [8], a methodology that takes into account the dependency of the electrical efficiency of the power plants with their capacity was applied, which improved the assessment of the potential of woody biomass wastes for electric energy generation made by Padilha et al. [4]. If the methodology of Padilha et al. [4] was applied to the data analyzed by [8], the electricity potential would be almost twice as large, 429.6 GWh $year^{-1}$. That difference in the energy potential calculated by the two methodologies referred above confirms the importance of considering the influence of the efficiency as a function of the installed power when estimating the electric energy that can be generated from wood residues.

The approach used to determine the electric energy potential of wood residues followed in work [8] considers not only the dependency of the efficiency on the installed power, but also the geographic location of the lumber mills, the amount of wood residues produced by each mill, and properties, such as the density and lower heating value, of the mixture of the wood residues produced locally.

Following the two works [4, 8], which applied two different approaches, the present study aims to consolidate the step-by-step methodology to estimate the electrical energy potential of residual biomass simultaneously considering the main variables that influence the result of the calculated electric energy generation. Those variables are the geographic location of the timber processing plants where the biomass residues are produced, the amount of residues produced in each of those plants, the density and lower heating value of the mix of the residues, and finally the dependency of the efficiency on the size of the power plants. To illustrate the application of the proposed methodology, a case study determining the potential of implementing biomass power plants fired with wood residues generated by the sawmills in the State of Pará—Brazil—was chosen and investigated. This work highlights the difference in the energy potential obtained when a variable electrical efficiency (dependent on the power) or a constant electrical efficiency is used. That methodological difference can have a great impact on the estimate of the electric energy potential of wood residues in the State of Pará such as the observed in previous works (235.5 GWh year^{-1} in [8] and 429.6 GWh year^{-1} in [4]).

2. Methodology for the evaluation of electric energy potential

Currently, combustion is the most widely used primary conversion technology of biomass into power and heat (it represents more than 90% of the installed capacity [9]). However, differently from heat, electricity can be integrated into the national grid. In general, steam turbines and the Rankine cycle are used for the conversion of biomass into electricity [10].

In the past, some studies published on the evaluation of the biomass energy potential, such as [4, 11–14], used a constant typical efficiency value. In their study, Brasil, Brasil Jr., and Malico [8] considered the electric efficiency dependence on the size of the power plant when calculating the electric energy potential of wood residues generated by the wood industry. That dependency of the efficiency on the installed power has also been presented, for example, by Bridgwater [15, 16], Dornburg and Faaij [17] and Caputo et al. [18]. Therefore, in order to achieve a more accurate calculation of the electric energy potential of biomass residues combusted in steam cycle power plants located at lumber mills, the efficiency must be a function of the power as proposed in [8]. Hence, the methodology proposed by the present work applies the same function of the efficiency dependency on the power as the suggested by [8].

When considering residues generated by the wood industry, other important variables with great impact on the calculation of the electric energy potential of wood residues are the properties of the mixture of wood species that are processed at the industrial sites and that can be used as fuel in steam cycle power plants of those sites. This is especially important in the Amazon region because the density and lower heating value (LHV) of the wood from the different tree species can vary significantly. It is worth to mention that the appropriate way to determine the residues energy content is multiplying the on-site LHV by the mass of residues.

However, for the evaluation of the electric energy potential of residual biomass, the power generation can only be determined if the power plant efficiency is known, and the efficiency is determined only if the generated power is known; so, the proposed methodology aims to address this circular problem.

2.1 Determination of on-site wood residues availability and properties

The first step of the proposed methodology for evaluating the electric energy potential of residual biomass from lumber mills is to gather the coordinates of the location of each mill operating in a study area, and then to store the locations using a geographic information system.

The second step of the methodology is to compute the availability and the properties of the residual biomass generated at each industrial facility. For that, the lumber mills are contacted and asked to provide relevant data. It is important to consider in the methodology what available data are registered and by the wood industries. In general, the available data that are essential to gather are the total trunk volume for each wood species received by the mill yearly, the total volume of processed wood sold yearly, and the total yearly operation hours. The available residues are calculated by the difference of the total trunk volume received and the volume of processed wood sold. Knowing which wood species are processed in the industrial plants, the wood density is determined from a database of wood properties and then the volume of residue for each species is multiplied by its density to obtain the mass. For the Brazilian wood species, the data from [19] and properties measured in laboratory published in [8] can be used.

The annual mass of wood residues on a dry basis of each species s generated by each lumber mill, $m_{s,i}$, is calculated by

$$m_{s,i} = \rho_s V_{s,i} \ , \tag{1}$$

where s means the s^{th} species processed in the i^{th} lumber mill that is located in the study area, ρ_s the basic density of each wood species, and $V_{s,i}$ the volume of wood residues of each species generated yearly by the i^{th} mill. The total mass of residues generated by each plant in 1 year is the sum of $m_{s,i}$ for all the species and the total mass of residues generated in a certain region, the sum of the wood residues generated in all the lumber mills located in that region.

2.2 Determination of the energy content of residues

For the determination of the energy content of the wood residues, similar to what was mentioned above for the wood density, a database is needed to determine the lower heating value on a dry basis, $\mathrm{LHV_{db}}$. Values of $\mathrm{LHV_{db}}$ for Brazilian species can be found in [8, 20].

After knowing the $\mathrm{LHV_{db}}$ and the mass of residues for each processed wood species, the next step of the methodology is to compute the energy content of the residues produced annually in the i^{th} industry located in the study area, E_i, calculated by

$$E_i = \sum_{s=1}^{N} m_{s,i} \, \mathrm{LHV}_{\mathrm{db},s} \tag{2}$$

where N is the number of species processed by the i^{th} lumber mill and $\mathrm{LHV}_{\mathrm{db},s}$ is the lower heating value on a dry basis of the wood species s processed by the i^{th} mill in the study area.

In Eq. (2), E_i represents the total energy content of the wood residues generated by the i^{th} lumber mill in 1 year. If the efficiency of conversion could ideally be 100%, this value would be the total electric energy potential of the i^{th} lumber mill. However, because this is not possible, E_i has to be multiplied by an energy conversion coefficient to determine the electric energy potential of residual woody biomass generated by the industry.

It is important to restate that the main idea of the present work is to propose a methodology focused on the conversion of the energy content of the residues generated by the wood industry into electricity by combustion followed by a steam turbine. Yet, although other final energy use and conversion technologies could be applicable for determining the energy potential of wood residues, the principle of multiplying the energy content of the residues by a conversion overall efficiency maintains. However, for other energy use and conversion technologies, the dependency of the efficiency with the size of the plant would be different from the function observed by [8, 15–18]. This is the case when the end energy use is heat, and that dependency would not occur.

In order to calculate the energy that could be generated from the wood residues and delivered to the electric grid every year, E_{out}, the overall efficiency of the energy conversion process, η_e, is defined in Eq. (3).

$$\eta_e = \frac{E_{\text{out}}}{E_i} \tag{3}$$

Typical efficiencies of small power plants with wood combustion and steam turbines are in a range of circa 15%, while larger power plants and those with recent technologies have efficiencies of 30% [21]. Efficiencies as high as 44% are reported by [22], but micro-scale systems operating with steam turbines can have efficiencies as low as 6–8% [23]. The work [4] estimated the electric energy potential of wood residues and considered a typical and constant efficiency value taken from the literature and did not account for the dependency of the efficiency with the installed power. As another example of this approach, Singh [11] considered two different efficiencies of 20 and 25% in converting agricultural residues to electricity, while Vukašinović and Gordić [12] considered an efficiency of 35%, and Weldemichael and Assefa [13] considered an electrical energy efficiency of 33%.

The present methodology proposes the curve for the overall efficiency as a function of the installed power suggested by [8].

2.3 Operating time of the power plant

As described in the two previous sections, the amount of wood residues and the energy content of these residues are determined yearly, and the efficiency depends on the installed electric power plant of a wood industry, the latter being defined by Eq. (4).

$$P_{out} = \frac{E_{\text{out}}}{t} \tag{4}$$

where t is the total yearly operating time of the power plant. Similarly, an ideal power can be defined by Eq. (5)

$$P_i = \frac{E_{\text{i}}}{t} \tag{5}$$

where P_i is the total energy content of the wood residues generated by the i^{th} lumber mill divided by the total yearly operating time of the power plant installed in that same plant.

Consequently, Eq. (3) can be rewritten as Eq. (6)

$$\eta_e = \frac{P_{\text{out}}}{P_i} \tag{6}$$

So, for the methodology proposed, the operating time of the wood industry power plants has an important impact on the calculation of the energy potential of wood residues.

2.4 Overall efficiency of residual biomass power plants

Instead of applying a constant value for the conversion efficiency, as already mentioned above, the present methodology recognizes the fact that the overall efficiency of a biomass power plant is expressed as a function of the power plant size, as done in [8]. However, the efficiency can only be determined when the generated power is known, and vice versa; so, a simple mathematical solution is used to overcome this circular reference problem. The procedure is illustrated in **Figure 2** and explained below.

The energy content of the biomass residues, whose calculation was explained in Section 2.2, is determined by Eq. (2). This total energy content of residues divided by the operating time explained in Section 2.3 results in an ideal power P_i defined by Eq. (5), which is represented by the circle number 1 in **Figure 2**, as if the efficiency of conversion would be ideally 100% (represented by circle number 2 in **Figure 2**). A conversion efficiency equal to 100% is not possible, but the value represented by circle number 2 is fundamental for the mathematical solution, establishing the linear equation crossing the origin and passing through the point of 100% efficiency, represented by the dark dashed line in **Figure 2**.

In the same **Figure 2**, the function of the overall efficiency with the installed power is represented by the solid line. The function represented in this figure is expressed in Eq. (7) and was proposed by [8] from a power law best curve fit to real data from Brazilian biomass-fired power plants and the published works of [15–18].

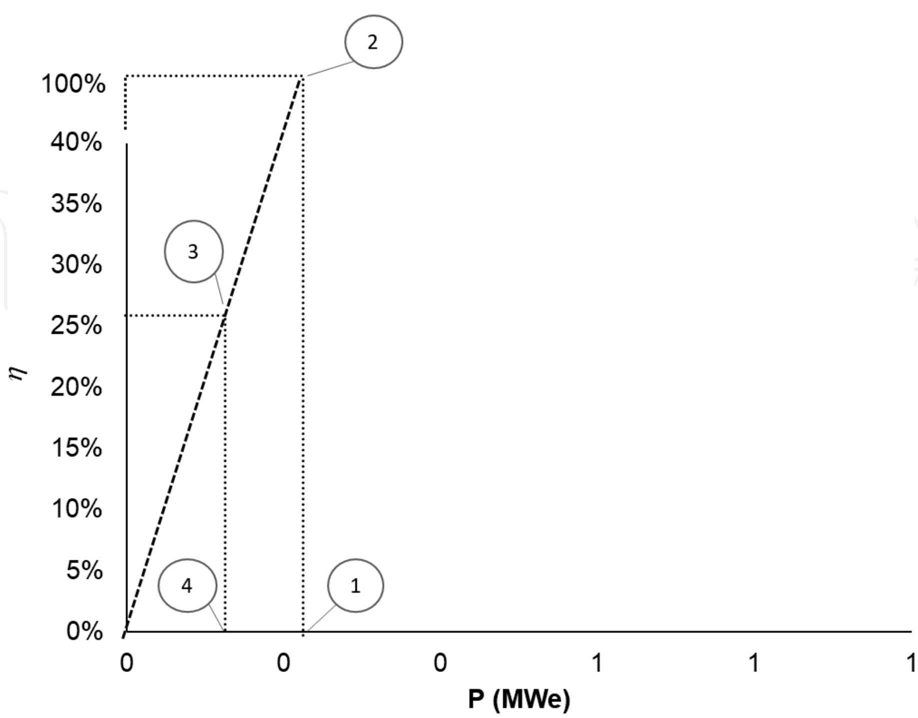

Figure 2.
Procedure used to calculate the efficiency and installed power of biomass-fired power plants—Solid line is the function of the overall efficiency with the installed power in Eq. (7) and dashed line is the linear equation crossing the origin and passing through the point of 100% efficiency.

$$\begin{cases} \eta_e = 0.0205 P^{0.2718} & \text{for } P < 250 \text{ kW}_e \\ \eta_e = 0.0363 P^{0.1877} & \text{for } 250 \text{ kW}_e \le P < 250 \times 10^3 \text{ kW}_e \end{cases} \quad (7)$$

where η_e is the overall efficiency of the biomass power plant and P the installed power in kW_e.

In **Figure 2**, circle number 3 represents the interception of the solid line function defined by Eq. (7), and the dashed line that passes through the origin and the point represented by circle number 2. So, the *x-y* values of the intersection represent, respectively, the real overall electric efficiency and the real installed electric power of a biomass power plant with a capacity equal to the value of circle number 4.

3. Application of the methodology

A case study was used to demonstrate the application of the proposed methodology detailed in the previous sections. For this purpose, the energy potential of the residual biomass generated by the wood industry in the State of Pará in Brazil was chosen. The present study used the data collected by a massive fieldwork carried out by the Brazilian Federal University of Pará, with results published by Padilha et al. [4] and Rendeiro et al. [24]. That fieldwork [4] collected data from 707 lumber mills in the State of Pará in order to evaluate the quantity of residues available for electric energy conversion. The study of Padilha et al. [4] established that the potential to install electric power plants in the factories processing timber in the State of Pará was 160 MW_e.

The present work identified that 32 out of the 707 wood processing plants generated virtually zero residues, so wood residues of 675 plants were available for electric energy use.

3.1 Location of residual biomass availability

As proposed by the methodology described above, the locations of the 675 lumber mills in the State of Pará were registered in a geographical information system. This location is shown with blue squares on **Figure 3**. These are all industrial facilities that generate biomass residues that can be valorized for energy. It is noticeable that the lumber mills are concentrated near the roads, because of the need to transport the products.

3.2 Biomass residues availability and properties

The data collected at all the lumber mills of the State of Pará were organized in a database containing the names and addresses of the companies, the geographic coordinates of their location, wood species processed, and the volume of residual biomass produced yearly for each of the wood species handled. Unfortunately, 108 plants only reported the total volume of wood processed and did not report the percentage of each wood species that was processed in that year. In order to overcome that limitation of not knowing the exact amount of wood species processed for these 108 plants and to fill the missing data, it was assumed that in these plants the composition of the processed species was statistically similar to the average of all the other plants in the state. This could be done because of the low variability of the species that are processed by all facilities in that region imposed by the commercial purposes to attend the market.

In accordance to what has been said, the basic density and LHV_{db} data of all species processed by the timber processing plants in the state was statistically analyzed in two histograms presented in **Figures 4** and **5**. The histogram of **Figure 4** shows the basic density of the species processed by the wood industry in the State of Pará and **Figure 5** shows the histogram of the LHV_{db} of the species processed by the wood industry in the state.

From the histograms of **Figures 4** and **5**, the statistical percentage of the basic density and LHV_{db} of species could be extrapolated to the missing data of 108 timber processing plants.

From the data referred before [4], which was gathered from the wood processing plants in the State of Pará in 2004, there were 49 different species processed by the industry. In work [4], samples of wood residues were collected onsite, the species were identified, and some properties measured in the laboratory of the Federal University of Pará. Proximate and elemental analyses were carried out and basic density and LHV_{db} measured. More details of the analyzed properties can be seen in [8]. The basic density of species was also confirmed by the values published in [19].

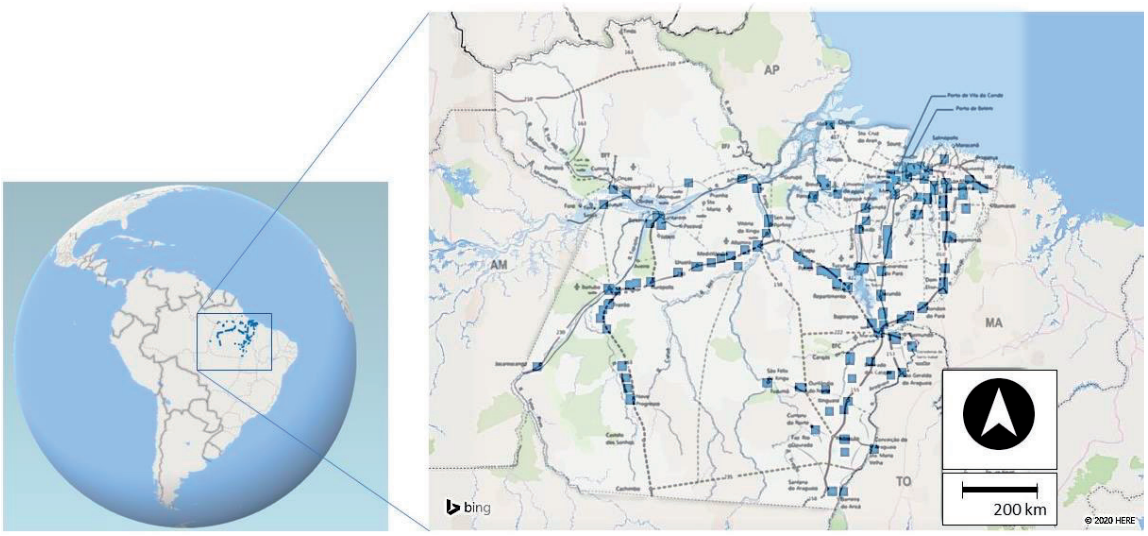

Figure 3.
Location of all lumber mills in the state of Pará—in blue squares.

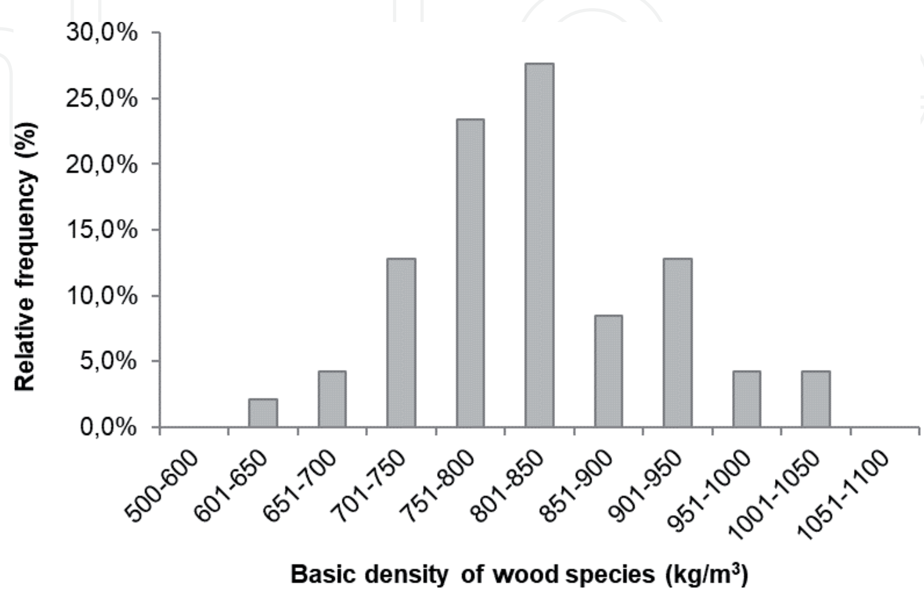

Figure 4.
Histogram of the basic density on a dry basis of wood species processed by the lumber mills in 2004 in the state of Pará.

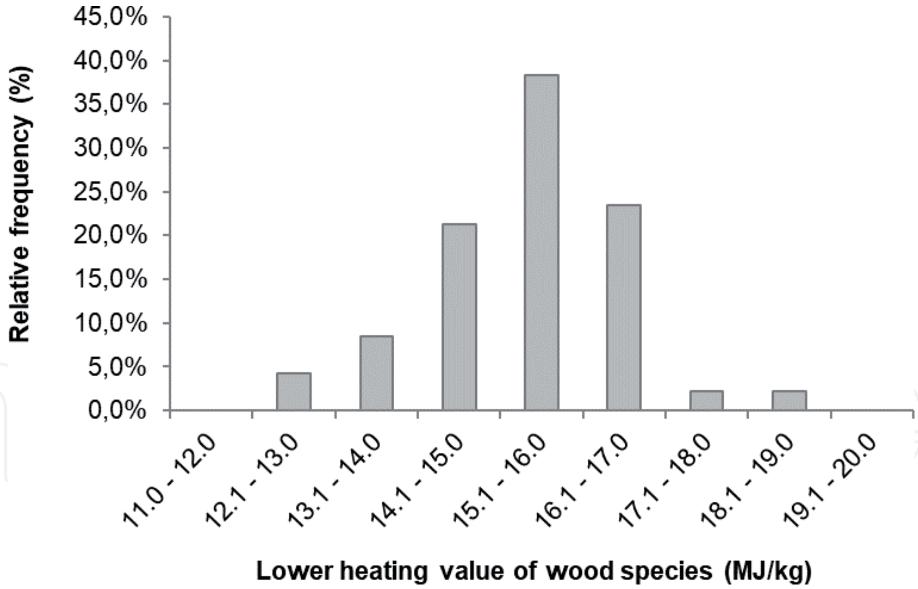

Figure 5.
Histogram of the lower heating value on a dry basis of wood species processed by the lumber mills in 2004 in the state of Pará.

As seen in Section 2.1, the available residues were calculated by the difference of the total trunk volume received in the plants and the volume of processed wood sold. The annual mass of residual wood of each species processed in each lumber mill was calculated by the sum of all species determined in Eq. (1). As a result, the total wood residues generated by the 675 lumber mills in the State of Pará in 2004 was 2.95×10^6 t in dry basis.

3.3 Determination of the energy content of residues

After knowing the annual mass of residues of each wood species in each lumber mill, the energy content, E_i, of the residual biomass in the i^{th} mill was calculated by Eq. (2). The total energy content available from the wood residues of the lumber mills in the State of Pará in 2004 was 12,557.5 GWh (this result was obtained by adding the potential for all the plants in the state).

3.4 Operating hours of the power plant

In Section 2.3, an ideal power was defined by Eq. (5), and for that, a yearly operating time needs to be established. In the State of Pará two different possibilities can be considered:

- The electricity is needed when the lumber mills are working. Typical working hours of the industry are 1760 h year^{-1} (10 months year^{-1}, 22 days month^{-1}, 8 h day^{-1}). The value of 10 months year^{-1} means a 2 months year^{-1} period when the lumber mills are not operating during the season of no timber cutting. This is a season when the lumber mills are on scheduled maintenance.

- The case of year-long operating biomass-fired power plants, when 2112 h of operating hours can be considered (12 months year^{-1}, 22 days month^{-1}, 8 h day^{-1}). This is the case for the industries analyzed in data collected by [4].

In this work, the ideal power P_i was determined considering 2112 h in Eq. (5) as the total yearly operating time of the power plants of the wood industry in the State of Pará. That ideal power defined the value of circle number 1 in **Figure 2** for each timber processing plant.

3.5 Overall efficiency of power plant from residues to electricity

Following the procedure described in Section 2.4, after knowing the ideal power represented by circle number 1 for 100% of efficiency, in **Figure 2**, and determining the point of circle number 2, the next step was to calculate point number 3 in order to determine the real overall electric efficiency and the installed electric power represented by circle number 4 in the same **Figure 2**.

The present methodology proposed a correlation function presented in Section 2.4, Eq. (7) and **Figure 2**, and compared the results obtained with the ones obtained using a constant value of 25% applied for the overall efficiency of the power plants, η_e in Eq. (3). In that case, the electrical energy potential would be determined by multiplying the energy content, E_i (for the residues of each i^{th} lumber mill) by 25%. This value was used by [4] and was chosen to compare the difference of two methodologies, for the same region and industries.

The present study compares the results of applying a constant value for the overall efficiency and the proposed methodology. **Figure 6** shows the histogram of the electric capacities that could potentially be installed in all lumber mills in the State of Pará. Light gray bars represent the electric power potential in kilowatt (kW_e) when a value of 25% is used for the overall efficiency, and dark gray bars, the potential of the electric installed power (kW_e) when the steps of proposed methodology are applied, as described in Section 2.4. When an operating time of 2112 h year^{-1} is considered, the total energy potential for the residual biomass generated by the wood industry in the State of Pará is 3140.4 GWh year^{-1} for the constant efficiency of 25% and 1868.8 GWh year^{-1} for the proposed methodology.

The results of the electrical energy potential presented above indicate that the use of the constant value for the efficiency considered overestimates the total predicted available energy, compared to the proposed methodology. Additionally, the modes of the two datasets in the histograms in **Figure 6** indicate that the highest

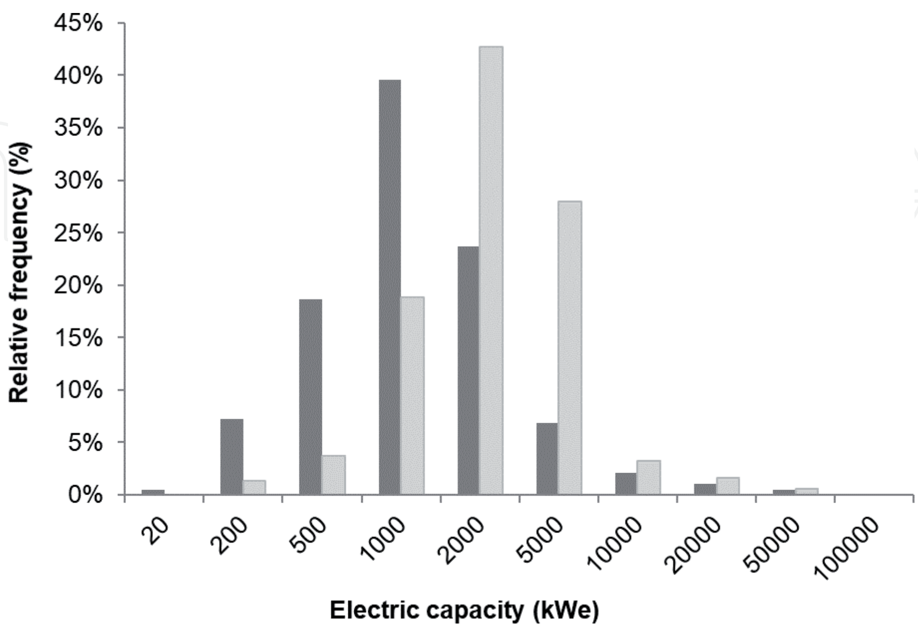

Figure 6.
Histogram of the electric capacity that can potentially be installed at lumber mills in the State of Pará, considering a constant overall electrical efficiency (light gray) and the dependency of efficiency with power (dark gray).

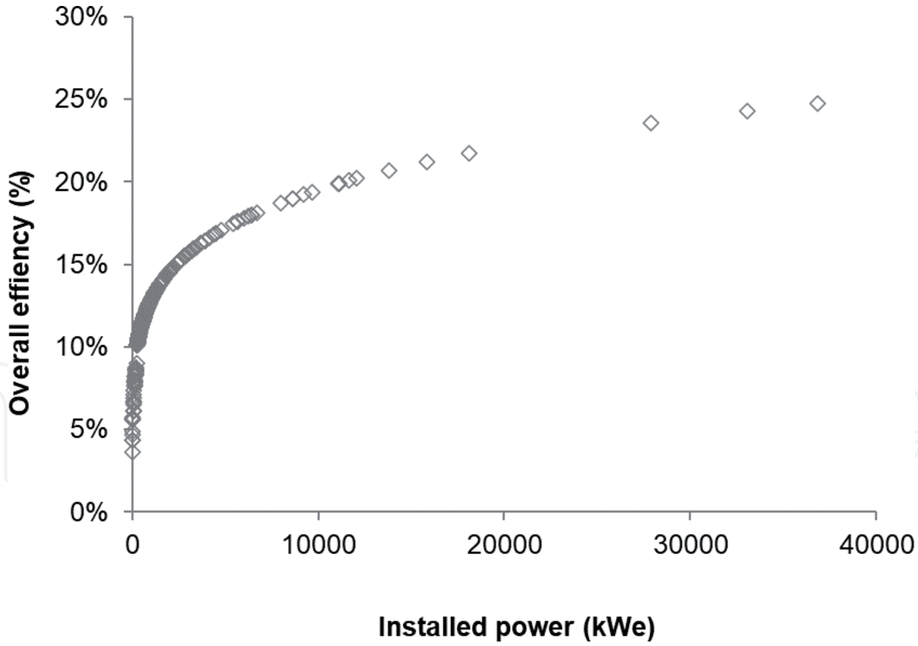

Figure 7.
Calculated overall efficiency as a function of the power for the 675 lumber mills that existed in 2004 in the state of Pará.

relative frequency is 42.7% at 2000 kWe for a constant efficiency value, and 39.6% at 1000 kWe for the proposed methodology. Also in **Figure 6**, summing the relative frequencies of potential capacities less than the mode value resulted in the conclusion that 66.52% of the lumber mills would have installed power up to 2 MW_e for a constant value of efficiency, while the proposed methodology indicates that 65.93% of the industrial units would have installed power below 1 MW_e. That conclusion is significant because one method indicates that most of the industries would have a power plant of 2 MW_e in comparison to 1 MW_e from the proposed methodology.

As presented in Section 2.4 and Eq. (7), the overall efficiency is a function of the installed power. Therefore, **Figure 7** shows the results of the efficiencies and potential capacities of the 675 wood industries in the State of Pará, indicating that an efficiency value of 25% is only applicable for power plants with capacities above 40 MW_e, which is never the case for the scenario in the State of Pará. The results of this case study confirm that a constant efficiency overestimates the electric energy potential when applying a constant value of 25% in Eq. (3) for all biomass plants and based on the total available energy content of residues. Nevertheless, when applying the efficiency as a function of the installed power, the resulting average efficiency is 12.3%, based on the values of efficiencies of all plants in **Figure 7**.

4. Conclusions

The present work systematized a step-by-step methodology to determine the electrical energy potential of residues generated by the wood industry. The application of the proposed methodology was demonstrated through a case study that analyzed the energy potential of the residues generated by the wood industry in the State of Pará in Brazil. In the past, several different studies considered a constant overall efficiency as a conversion factor from residues to electricity. The proposed methodology suggests an overall efficiency as a function of the installed power, with data correlation obtained from a best curve fit of real data both taken from the literature [15–19] and from Brazilian biomass-fired power plants.

The data for the case study was collected in 2004 with results published by Padilha et al. [4] and Rendeiro et al. [24]. The work of Padilha et al. [4] collected data from 675 timber processing plants in the State of Pará, which generated an amount or wood residues equal to 2.95×10^6 t on dry basis in that year. In this work, the energy potential of these residues was calculated in two different manners for the sake of comparison: (1) similar to what was done in [4], a constant overall conversion efficiency of 25% was considered; and (2) the methodology presented in this work was used (i.e., the efficiency is a function of the size of the plant).

As a conclusion, the electrical energy potential is overestimated when a constant overall efficiency of 25% is used (3140.4 GWh year^{-1}) in comparison to the one obtained for the proposed methodology (1868.8 GWh year^{-1}). Concerning the power that can potentially be installed to valorize the residual biomass, when a constant efficiency was applied; the results indicate that most of the power plants would have a 2-MW_e capacity, while for the proposed methodology the results indicate that most of the power plants would have a capacity of 1 MW_e. Moreover, in agreement with the function presented in this work for the dependency of the efficiency with plant size, a 25% efficiency is only applicable for power plants with a power as high as 40 MW, which is never the case for the wood industry in the State of Pará. The results of the methodology proposed in this work highlight the importance of using the overall electrical efficiency as a function of installed power when determining the residual biomass potential.

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Author details

Augusto César de Mendonça Brasil
Energy Engineering, University of Brasília at Gama, Brasília, DF, Brazil

*Address all correspondence to: ambrasil@unb.br

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