Determination of the Optimal Size and Location of an Electricity Generation Plant that Uses Lignocellulosic Residues from Costa Rican Northern

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Abstract
The northern zone of Costa Rica has extensive forestry and agro-industrial development, which generates a large number of lignocellulosic residues that do not have an economic value but could represent a vast energy potential. Therefore, the objective of this study was to determine the optimal size and location of an electricity generation plant from the forest and agro-industrial biomass. The researchers worked with two forest species residues (Gmelina arborea and Tectona grandis) and two agro-industrial residues (Ananas comosus and Saccharum officinarum), representing the most extensive cultivations in the region. The material was characterized, then GIS layers of the species cultivation areas were analyzed and related to the roads and protected areas to define the twelve potential points where the power plant should be installed. Later, the optimal supply radius of the plant and the optimal site conditions were determined. The study determined that the tree species have an average caloric power of 19,059.50 kJ/kg, significantly higher than agro-industrial (16,684.9 kJ/kg). It was determined that 1,056,527.67 tons of dry biomass are generated per year; 6.5% arboreal and 79.97% from A. comosus. The minimum electricity generation capacity is 15 MW with an annual consumption of 102,300 tons, which are available between 15 and 100 km away from the sites. The southeast area was the best positioned because of the biomass source and optimal environmental conditions for establishing the power plant.

Keywords Bioelectricity · Dry biomass · Lignocellulosic residues · Costa Rica

Introduction
Lignocellulosic biomass is defined as dry plant origin material [1], considered a viable alternative energy source to fossil fuels or natural gas [2]. The ease of generation of biomass from agro-industrial and forestry crops, the low CO₂ emission, the simplicity of storage and use and management together with the energy potential of productive residues [3], make the biomass an optimal energy source for developing countries that have large agro-industrial and productive forest areas [4]. It is estimated that biomass supplies about 10.4% of world energy demand, and for the next decade, an increase of 16% is expected [5].

Valverde et al. [6] mentioned that biomass could be transformed into electrical energy through thermochemical processes such as combustion, pyrolysis, liquefaction, or gasification, focused on self-sufficiency or energy sale for commercial purposes. The cost of energy from biomass varies related to the technology used and based material. Sometimes its low cost is because residues from a productive system that do not have an economic value are used. If not used for energy production, the residues would be burned, sent to landfills, or buried [7].

Consequently, including them in a subprocess allows improving the efficiency of the material and generating a
lower environmental impact, causing economic and environmental benefits in rural communities [8]. Zhang et al. [9] highlight that the residual agricultural biomass for power generation is abundant; for example, about 60% of the sugarcane and rice plant are not used in the production system. Kinoshita et al. [10] emphasize that the tree biomass from pruning or thinning in the first years of cultivation tends to be discarded, which could represent a high percentage of raw material for energy generation.

In order to maintain biomass energy competitiveness against other renewable sources (hydro or thermal) and nonrenewable sources (fossil fuels or natural gas), biomass generation must ensure a low financial cost. Sahoo et al. [11] and Sharma et al. [12] highlight that to ensure the competitiveness of this energy source, three main elements must be taken into consideration: caloric power of biomass (heat generation capacity for energy purposes), moisture content of biomass (must be less than 30% for efficient use), and location of the power generation plant from the sources of biomass origin (in order to keep the transportation cost as low as possible). This last variable is the most relevant in reducing costs in biomass generation systems; since the cost of transportation could represent 35% of the final cost of the electricity generation, according to Viana et al. [13] in generation plants in Portugal.

In addition, the quantification of waste products in the productive areas, identifying the areas with greater ease of access, and the installation of biomass processing zones are fundamental factors to determine the potential costs of an energy project [14]. Therefore, geographic information system (GIS) represents a powerful tool for integrating biomass generation information, simplifying the study, and selecting optimal areas to establish power generation plants [15]. The potential of GIS to relate spatial and productive data has been widely used in the last decade. Shi et al. [16] in Guangdong, China, determined that to have a competitive electricity generation price, the maximum biomass transport distance should be 60 km. On the other hand, in Portugal, Viana et al. [13], using this same technology, determined three specific points for developing a power plant. Hiloidhari et al. [17] in India determined the installation points of biomass reception plants from the road network to create a sustainable biomass production network. Finally, Lozano-García et al. [8] determined the development of areas for energy plantations that could supply an already installed plant in order that within 3 years, the plant would have a stable source of biomass and that in the process, the existing wild areas would be protected.

Given the potential for using GIS to determine productive biomass areas in Costa Rica, it opens the possibility of creating layers of information that allow planning and sustainable use of biomass as a long-term energy source. However, there are no clear studies that implement GIS in the tropical region to optimize power plants. Therefore, in the present study, the size and optimal location of an electricity generation plant from the forest and agro-industrial biomass in the northern zone of Costa Rica was determined.

Materials and Methods

Study Site and Crops

The study was carried out in the northern zone of Costa Rica (10°20′–11°48′ N) and (84°10′–85°26′ W), which has an area of 7030.86 km² and is characterized by a wide productive agricultural and forestry development. The annual temperature varies between 28 and 32 °C; the annual relative humidity varies from 60 to 95%, with an annual rainfall of 1800 to 4200 mm and a rainy season of 7 months distributed from May to November.

This study analyzed residues of forest and agricultural crops left in the field due to management and harvesting activities. The forest level analyzed the two forest species with the most significant area planted in the zone: *Gmelina arborea* and *Tectona grandis*. The georeferenced information used for both species was based on the National Forest Inventory of 2014. In agro-industrial crops, greater economic importance and more significant extension in the area were analyzed, represented by *Ananas comosus* (pineapple) and *Saccharum officinarum* (sugar cane). For *A. comosus*, it was implemented the georeferenced layer (GIS) of crop distribution developed by PRIAS in 2019, while the information of *S. officinarum* came from the study of Chaves and Chavarría [18].

Biomass Estimation at the Study Site

Field sampling was conducted to determine the amount of biomass waste generated by the crops. Twelve sites per crop were selected from the information obtained through the GIS layers, and random sampling was developed. The determination of the intensity of the sampling by biomass type was developed according to the methodology proposed by Valverde et al. [19] for biomass analysis in Costa Rica, with a statistical significance of 95%.

In each site, six rectangular plots of 100 m² were established, in which all the biomass considered the residue was weighed in the case of forest species, all the remaining branches and trunks from pruning and thinning, and for agro-industrial crops, all the residues from handling and harvesting. A sample composed of 500 g of biomass was taken from each site and estimated the caloric power, moisture content, and ashes.
Determination of Caloric Properties and Humidity of the Study Crops

From each crop, a sample composed of 500 g of material was collected. The sample was pulverized with a mill and then used to determine the superior caloric power, moisture content, and ashes. The superior calorific power was developed under the ASTM D-5865 standard [20], which proposes to dry the material for 48 h using a furnace and, later to sift it to generate a particle size of 0.25 to 0.52 mm, from which three subsamples of 5 g of material were extracted. In order to have representative data of each analyzed waste, we worked with the triplicate mode.

The moisture content was determined through the ASTM D-4442 standard [21], weighing the twenty samples of residues in green condition and drying them in an oven for 24 h at a temperature of 103 °C. This generated the dry weight that was used in Eq. 1 for the calculation of the moisture content. Finally, the ash content was determined with the ASTM D 1102–84 norm [22].

\[
MC = \frac{GW - DW}{GW} \times 100
\]  

where MC is moisture content (%), GW is green weight (g), and DW is dry weight (g).

Establishment of Potential Sites for Power Plants

Due to the region’s size and the numerous potential locations for the electric power plant, a shortlist of twelve sites that presented the possibility of meeting the minimum conditions for installing the infrastructure was drawn up (Fig. 1). The elements considered in this preselection were flat topography, availability of public services (water, internet, and public transport), and compliance with national legislation for the development of energy activities without affecting communities; each site was evaluated with the methodology of Valverde et al. [19] had to comply with the selection aspects to be preselected fully.
Minimum Sustainable Production of the Electricity Generation Plant

Previous studies developed by González et al. [23] determined the minimum technical and financial characteristics for a biomass generation plant to be functional in Costa Rica (both for electricity generation for self-supply and sale to the national electricity market); the requirements are presented in Table 1. This study carried out a comparative analysis of different levels of energy productivity (10, 15, 20, 25, 30, 40, and 50 MW), estimating the amount of annual biomass needed and the financial indicators (annual net value (ANV), internal rate return (IRR), and benefit–cost ratio (BCR)) that the development of a power plant would have with each level of productivity. Finally, the minimum productivity that showed values higher than those recommended by González et al. [23], this under the premise of previous studies in the tropics recommend the installation of power plants to be developed in phases depending on whether the investment is distributed over time, the first phase being the installation of a minimum electricity generation plant but financially profitable [3, 4, 19].

Maximum Distance of Biomass Availability

From each potential point for the installation of the generation plant (Fig. 1), the maximum supply distance was determined, using the information of the minimum annual biomass required, the capacity of the cultivation areas (with their respective available biomass), and the highway network of the region. For the distance projection and biomass supply, the QGIS fTools was used according to Gonzales et al. [23].

Together with the distance determination, the financial viability of biomass acquisition was analyzed. The information from previous studies developed by Ulloa et al. [3] in Costa Rica, in which it determined that the market price of biomass is USD 62/ton of dry biomass (this market value considers: collection, transformation to chips, drying, and transport up to 21 km away from the site), with the detail that each extra kilometer of transportation represents a value of USD 0.7/km/ton dry biomass. It is considered that the maximum recommended distance according to Ulloa et al. [3] would be 30 km due to estimates of profitability for the purchase of biomass for Costa Rica. The analysis primarily determined the amount of biomass in the range proposed by Ulloa et al. [3] and, subsequently, what is the maximum supply distance necessary to satisfy the biomass necessary for the necessary electrical generation.

Variables for Determining the Best Plant Location

First, locations that do not meet the minimum biomass supply conditions will be discarded. Second, the prequalified areas were subjected to Ulloa et al. [3] since this methodology shows the best adaptability for Costa Rica. Project conditions (Cp), in which five variables were analyzed: road network conditions (capacity of the road network to support the continuous movement of trucks); electrical network connection (that an electrical distribution network is available with the conditions to connect to the project); the closeness of industries and towns (in order to have labor and potential energy-demanding market), and distance from conservation areas (that the project does not generate an impact on protected areas). Each variable was evaluated with the methodology of Ulloa et al. [3], five bioenergy specialists in the tropics carried out the evaluation, each variable was given a percentage value from 0 to 20%, with 20% being the maximum value; later, the values of the five variables were added to estimate Cp.

Subsequently, the determination of the plant potential localization (Ppl) Eq. 2 was used. The Cp value was used, which was assigned a weight of 40%, and the volume of biomass available (Vb) is the relationship between the percentage of biomass available at 21 km from each point (maximum distance considered in the transportation of biomass

| Requirement | Aspect                                      | Minimum value                                      |
|-------------|---------------------------------------------|---------------------------------------------------|
| Technical   | Technology type                             | 2nd generation boiler                              |
|             | Biomass transformation efficiency           | 70–75%                                            |
|             | Biomass type                                | General (forestry and agro-industrial), maximum    |
|             |                                              | dimensions of 40 mm, compatible with pellets       |
|             | Maximum moisture content allowed by the system | 30%                                              |
|             | Voltage and electrical frequency required   | 120/240 V; at 50 or 60 Hz, in one, two, or three phases |
| Financial   | Annual net value (ANV)                      | 15.0                                              |
|             | Internal rate return (IRR)                  | 4.0                                               |
|             | Benefit–cost ratio (BCR)                    | 1.0                                               |
that is paid within USD 64/ton). The Ppl value obtained ranged from 0 to 100%, considering that the higher the value, the more ideal the site conditions.

\[ Ppl(\%) = (0.6 \times Vb + 0.4 \times Cp) \]  

where Pp is power plant potential localization (%), Vb is the volume of biomass available, and Cp is conditions for project development.

**Information Management**

The crops’ information layers, together with the determination of the supply distances and the power plant’s optimal location, were carried out in the program QGIS version 3.1.4. As for the homogeneity analyses within the data of moisture content, calorimetry, ash, and characterization of the site, an analysis of variance (ANOVA) with a significance of 0.05 was carried out, using the program R version 3.6.2 [24].

**Results**

**Characterization of the Caloric Properties of the Residues**

The characterization of the superior gross calorific value presented a variation between forest biomass and agro-industrial biomass (Table 2). The gross calorific value of *G. arborea* and *T. grandis* showed an average value of 19,059.50 kJ/kg. *A. comosus* and *S. officinarum* was 16,684.9 kJ/kg. As for the moisture content, the forest species presented an average value of 80.33%, a lower value than the agro-industrial crops, which was 90.22%. Finally, no significant differences were found in the ash content between the four crops, showing an average value of 5.31%.

The available forest biomass showed high moisture values due to the high humidity and rainfall conditions in the region, in addition to the fact that trees tend to be cut and left whole in the field (the crown is not cut or separated from the tree canopy), which slows the drying of the biomass. In the case of agro-industrial species, they tend to be the whole plants or segments of them, which are not dried and are left in the field or in the industry without opportunity for drying, their humidity is high, in combination that their storage is in the open air, managing to conserve the water that falls in the rain.

**The Energy Capacity of Available Biomass**

When analyzing the generation of residual biomass (Table 3), it was determined that forest cultivation generated 16.5 tons/ha, which comes from the branches cut in the pruning processes, treetops, and trees that do not meet the minimum harvest diameters. With this, it is possible to find annually about 68,585.5 tons of residual biomass, representing in power the base of an electrical generation of 16.32 MW (with an efficiency of 70%).

In the case of *A. comosus*, the annual generation per hectare of dry residual biomass was 34.1 tons, coming from the handling and harvesting of the crop (the whole plant becomes a residue). These data annually represent 845,500 tons of dry biomass, which currently have no productive use (burned or buried). On the other hand, its use for the production of electrical energy could represent 153.72 MW. Finally, *S. officinarum* generated 24.6 tons/ha/year of residual biomass, coming from harvest residues such as the plant leaves. Taking advantage of these residues could mean an annual contribution of 26.37 MW to the national electrical system.

![Table 2](image)

| Biomass type | Caloric power (kJ/kg) | Moisture content (%) | Ash (%) |
|--------------|-----------------------|----------------------|--------|
| *G. arborea* | 18,518.3 a (368.4)    | 81.53 b (9.44)       | 4.34 a (2.11) |
| *T. grandis* | 19,600.7 a (690.0)    | 79.13 b (9.89)       | 3.99 a (1.02) |
| *A. comosus* | 17,189.3 b (789.9)    | 92.30 a (7.34)       | 5.90 a (1.23) |
| *S. officinarum* | 16,180.5 b (867.6) | 88.14 a (8.87)       | 6.99 a (1.53) |

Values in parentheses correspond to standard deviation. Different letters indicate significant differences at 0.05

![Table 3](image)

| Biomass type | Dry residues generated (tons/ha/year) | Cultivated area (ha) | Available dry biomass (tons/year) | Energy potential (MW) |
|--------------|---------------------------------------|----------------------|-----------------------------------|-----------------------|
| Forestry     | 16.5 (3.2)                             | 4156.70              | 68,585.55 (13,301.44)             | 16.32 (2.96)          |
| *A. comosus* | 34.1 (5.6)                             | 24,794.72            | 845,500.00 (138,850.42)           | 153.72 (28.34)        |
| *S. officinarum* | 24.6 (5.9)                  | 5790.33              | 142,442.12 (34,162.97)           | 26.37 (7.11)          |
| Total        | -                                     | 34,921.75            | 1,056,527.67                      | 196.41                |

Values in parentheses correspond to standard deviation
Minimum Sustainable Production of the Electric Generation Plant

It was determined that the minimum electricity generation capacity for the profitable generation of energy in the northern zone of Costa Rica is 15 MW (Table 4). With lower capacities, installing power generation plants would not have financial profitability with the current biomass sales price of USD 64/ton. Plants with a higher electricity generation show better indicators, but under the premise of the study by González et al. [23], recoverability starts at 15 MW so that a first phase would be an ideal capacity. With this minimum level of energy production is necessary 102,300 tons/year, a single annual agro-industrial waste would be required to use an area of 3000 ha of A. comosus or 4185 ha of S. officinarum, if only forest residues were used, it would be 6200 ha per year, if the different waste of the required annual area would vary, depending on the location.

The study shows that establishing power plants with a capacity greater than 30 MW does not significantly increase NPV and IRR, so their development would generate more significant pressure on biomass supply. However, this could be a risk depending on the market variations in the medium and long term, so a plant with electricity generation between 15 and 30 MW would be financially feasible and would consume a reasonable availability of biomass, with the opportunity to grow its electricity generation over time.

Determination of the Maximum Biomass Supply Distance

When analyzing the maximum biomass supply distance to supply the 15-MW power generation plant (Table 5), it was determined that sites 4, 7, and 11 have a distance less than 25 km (average 21.0 km), being sites with ease of supply and capacity to expand their biomass supply between 10 and 25%. On the other hand, sites with a distance of up to 30 km would require a decrease in biomass purchase prices, the development of new crops close to the area, or an increase in electricity sales prices. Points 2, 5, 6, 8, 10, and 12 require greater distances, between 38 and 50 km, so they were considered low viability sites under the current costs of biomass sales and energy marketing in Costa Rica. On the other hand, sites 1, 3, and 9 require up to 50 km of distance to supply the necessary biomass, being considered nonviable sites for installing the power plant.

The main source of supply for point 11 would be 85.5% A. comosus, 12.5% S. officinarum, and 2.0% forest; in the case of point 7, it would be 18.8% forest, 3.0% S. officinarum, and 84.0% A. comosus. Finally, for point 4, it would be 70.5% A. comosus, 22.4% S. officinarum, and 7.1% forest. In these sites, biomass availability in the first 15 km of the road varies between 60 and 96%. If the road distance increases to 30 km, the site with the highest biomass availability would be 11 with increased potential of 40,000 tons/year, whereas site 7 would be 30,000 tons/year, and sites 4 and 7 would be barely 28,500 tons/year.

Optimal Location of the Bioelectric Generation Plant

Analyzing the conditions of the sites (Table 6), it was determined that sites 7 and 1 have the best road structure conditions, whereas site 4 showed the most deficient conditions. In terms of electrical connectivity, only site 4 shows limitations in its possibility of connection because the area does not have a connection system to the national electricity grid. For its part, the proximity of industrial areas, all sites show proximity to packaging and food processing, metallurgy, and forestry industries. Finally, in terms of proximity to the conservation area, location 4 is the most susceptible, as it is close to protected areas.

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**Table 4** Annual biomass requirement and financial indicators to determine the minimum electrical capacity for a plant that uses biomass in the northern zone of Costa Rica

| Electricity generation (MW) | Necessary dry biomass (ton/year) | ANV | IRR | BCR |
|----------------------------|---------------------------------|-----|-----|-----|
| 10                         | 68,200                          | 9.5 | 3.0 | 0.32|
| 15                         | 102,300                         | 17.7| 5.2 | 1.20|
| 20                         | 136,400                         | 19.9| 5.4 | 1.21|
| 25                         | 170,500                         | 23.6| 7.3 | 1.30|
| 30                         | 238,700                         | 28.5| 8.9 | 1.42|
| 40                         | 272,800                         | 28.7| 9.1 | 1.46|
| 50                         | 375,100                         | 28.9| 9.2 | 1.48|

**Table 5** Maximum distance by road to access biomass and percentage of biomass available for each point preselected for the installation of a biomass power plant in the northern zone of Costa Rica

| Site  | Maximum distance (km) | Percentage of biomass availability |
|-------|-----------------------|-----------------------------------|
|       |                       | Forestry | A. comosus | S. officinarum |
| 1     | 80.3                  | 30.2     | 55.3       | 14.5          |
| 2     | 40.3                  | 10.2     | 84.6       | 5.2           |
| 3     | 52.3                  | 5.0      | 50.3       | 44.7          |
| 4     | 24.9                  | 7.1      | 70.5       | 22.4          |
| 5     | 44.5                  | 15.5     | 60.0       | 24.5          |
| 6     | 48.9                  | 30.2     | 45.9       | 23.9          |
| 7     | 22.8                  | 13.0     | 84.0       | 3.0           |
| 8     | 49.9                  | 6.5      | 60.9       | 32.6          |
| 9     | 80.2                  | 5.5      | 93.5       | 1.0           |
| 10    | 41.7                  | 2.2      | 75.5       | 22.3          |
| 11    | 15.3                  | 2.0      | 85.5       | 12.5          |
| 12    | 38.2                  | 2.0      | 60.7       | 37.3          |

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(\cite{23})
Therefore, when analyzing the Ppl (Table 7), it was determined that site 11 is the optimal site for the installation of the power plant because it is the one with the highest biomass availability and has the ideal site conditions as a whole that shows ideal conditions for a potential increase in biomass consumption. The second option for installing the power plant would be site 7, which showed deficiencies in the road network and more limitations in case of requiring an increase in biomass consumption. Finally, site 4 would be less viable due to the limitations of connection to the electricity grid and the proximity of conservation areas.

**Discussion**

**Biomass Conditions for Electricity Generation**

The study determined that the biomass of the four species exceeded 15,000 KJ/kg. According to Ogorure et al. [25], this was considered high energy capacity biomass, thus allowing the energy use with the limitation that the moisture content was above 80% in all species. This makes it necessary to develop a drying process of the biomass so that the humidity of the biomass was less than 30% and the combustion process was acceptable (humidity contents higher than 30% decrease between 40 and 60% the energetic capacity of the biomass [26]. Furthermore, Kosse et al. [7] recommend placing the bioelectric plant close to the biomass generation areas to decrease the cost of transporting wet biomass (which would increase the generation costs). Kaundinya et al. [27] mentioned that biomass generation should be developed with low-cost processes of moisture homologation, either with solarization techniques, the use of gasses or heat from boilers, and an increased storage period of biomass.

Another important element to consider in the use of biomass was the size of the material to be contributed to the boiler. Since the biomass understudy was so varied (forestry and agro-industrial), it would require a transformation process, either in pellets or particles, so that the biomass was as homogeneous as possible, and thus the combustion process was continuous. Ogorure et al. [25] mentioned that in the generation of bioelectricity, the homogeneity of the size of the particles is fundamental so that the energy consumption of combustion does not increase, and with it, the boiler’s performance decreases. According to Farrell et al. [26], this is fundamental in the design and development of boilers. The boiler is designed for optimal combustion performance according to the material. Using heterogeneous materials will decrease energy productivity by 5 to 40%.

In the study area, it was determined that the predominance of biomass is agro-industrial waste, which has lower energy values but greater abundance, so that, the use of a boiler-type electricity generation plant would require an adaptation to the waste of both species. Valverde et al. [19] highlight that the provision of equipment adaptable to different species allows maintaining the continuous flow of electricity generation and an adaptation to market availability, but it will depend on continuous maintenance and the development of homogenization of biomass conditions such as the moisture content, residue size, and biomass administration flow. Aspects that Arias et al. [5] recommend is considering the use of residues in tropical regions.

**Importance of Biomass Distance in Power Plants**

The range of biomass supply to the power plant is a relevant factor when selecting the location of the facilities. In sites with a dispersed distribution of biomass, such as the study region (Fig. 1), the range of supply was relevant to the energy project: areas with low biomass availability will either decrease generation or increase the supply area so that biomass transportation costs will increase. Kinoshita et al. [10] and Flores-Marco et al. [28] mentioned that the
installation of the plant should consider the lowest displacement of the raw material. To reduce costs, make a planned process in which biomass availability is constant over time, and the impact on roads and towns is minimal. Dalla-Longa et al. [29] emphasized that the biomass near the power plant simplifies transport planning, increasing the volume of biomass transported daily, which would impact the need for less investment in biomass storage. This can generate a decrease in the fixed costs of electricity generation. The defined distance of 30 km (Fig. 1) was a contrast to Jayaratna et al. [30], who recommended 100 km, and Viana et al. [13] with 35 km; the differences are due to the electricity and transportation costs of each country in addition to the maximum available energy capacity of the regions under study.

In the study, the use of biomass at a distance of less than 30 km is ideal due to the high cost of biomass commercialization, an aspect that limited most of the sites analyzed that have a significant amount of biomass between 38 and 50 km. This has an impact on the costs of electricity generation, the possibility of having a greater source of biomass suppliers and being able to have a potential growth in electricity generation or in case of an increase in biomass price, being able to analyze distance reduction and its impact on the offer. Gonzales et al. [23] highlight that the availability of the proximity of biomass not only affects costs, facilitates the logistics of biomass delivery, reduces the time and areas for material storage, and simplifies logistics; in addition, the impact of transport will be less for the nearby communities. This aspect was shown in the study to be a strong point since the proximity of biomass sources would generate a minimum biomass storage time since delivery times would be very short.

GIS in Determining Optimal Power Plant Points

Georeferencing the areas of biomass production, knowing the capacity of waste generation in conjunction with aspects such as electrical connection, road network, and conservation areas allows the definition of optimal areas for the establishment of power generation units. Höhn et al. [31] and Kaundinya et al. [27] emphasized the need to have multivariate information for decision making in power plants in order to count the most significant number of technical criteria at the time of installation of a plant and avoid errors in location or consideration of ease of energy sources or electrical connection, for the study area with its wide dispersion of biomass sources, being able to select an area of high productive concentration allows not only to generate more electricity production but also to reduce the costs of generation by transport.

Zyadin et al. [15] and Jeong and Ramírez-Gómez [32] highlighted that having geospatial data concerning energy productivity for the tropical region allowed knowing the areas of energy accumulation bioenergy processes should be a priority. It also defined possible biomass storage points and areas of low intervention due to low productivity. For its part, Yoshioka et al. [33] mentioned that the dimensionality that generates the georeferenced information allowed the optimization of the logistics of biomass movement and defined the shifts of harvesting and collection of material. This prevented regions with abrupt topography or infer in low yields and decreased the ability to define priority areas. Teixeira et al. [34] in Portugal determined that the possibility of defining the regions with the highest concentration of biomass allowed for the design of power plants that have an appropriate capacity and categorize the areas according to energy priority, which avoids investing in low productive or high-cost areas.

In the study, the use of GIS tools simplified the process of locating the optimal site, in addition to allowing the determination of the distances of biomass availability and conditions for the installation of the plant, aspects that according to Ulloa et al. [3] were considered critical in the development of electricity generation. With biomass, being able to reduce transportation costs leads to an increase in the profit margin in electricity generation, as well as simplifying logistics. In the study site in the northern and western parts, the biomass dispersion is greater than in the eastern and southern parts, so relating spatial distribution with knowledge of the site conditions improves the selection and viability of the project [19].

In the tropical region, the generation of energy with biomass has not considered the proximity of biomass sources or the conditions of the infrastructure [4], which influence the high prices of electricity generation and lower profit margins, an aspect that the study improves significantly through the use of GIS tools in conjunction with a broad knowledge of the available biomass and its location. As more information is available in the most optimal way, the decision-making capacity will be better [19], so the selection of the chosen site will have a greater functionality to have biomass and be able to connect to Costa Rica’s electricity grid, with a competitive capacity in terms of electricity sales price [6].

Conclusions

It was determined that the tree species of the study have an average caloric power of 19,059.50 kJ/kg, significantly higher than the agro-industrial ones of 16,684.9 kJ/kg. Furthermore, the moisture content in the arboreal species is 80.33%, and for the agro-industrial crops, 90.22% with an average ash commitment of 4.16%. In terms of biomass generation, the study area generates 1,056,527.67 tons annually, with A. comosus generating the most significant biomass
representing 79.97%, while forest species only 6.5%; enough biomass to generate 196.41 MW of electricity.

The minimum electricity generation capacity must be 15 MW, which would be economically viable, an aspect that led to only three preselected sites being considered. Therefore, the optimal point was found to be point 11, located in the southeast of the region, with a biomass distance less than 20 km, and which has the best conditions in the region in terms of accessibility to roads, electrical connection, proximity to towns, industry growth potential, and distance from conservation areas.

The use of GIS tools together with the characterization of the biomass in the area facilitated the determination and sizing of an electrical power plant from biomass, an aspect that has a greater impact on the viability of this type of project, simplifying logistics and defining the minimum conditions necessary for the use of waste for electricity generation, an aspect that is essential to continue this line of research in tropical regions.

**Author Contribution** JCV, DA, and RC developed the concept of the study; JCV, CM, MF, and LB collected the information; JCV performed the statistical analyzes; all authors participated in the writing and proofreading of the article.

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**Data Availability** The data analyzed in this manuscript are available from the corresponding 280 author upon request.

**Declarations**

**Ethics Approval and Consent to Participate** All the authors have actively participated in the publication. They agree on the information provided and that ethical standards have been respected in the generation of the information. They also agree to be part of the authors of the article.

**Consent for Publication** All authors agree with the publication of the manuscript according to the journal’s policies. They have accepted the observations given and respect the associated regulations for the publication of the research.

**Competing Interests** The authors declare no competing interests.

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