Chapter

Silvopastoral Systems for Energy Generation

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Abstract

The silvipastoral systems are characterized by the association between tree crops, pastures and animals and can also constitute an efficient and sustainable means of supplying forest biomass for energy purposes such as electric, mechanical and thermal energy generation. It is an unconventional energy alternative and the evaluation of the energy potential offered by this productive system depends on several factors, such as management techniques, forest species, silvipastoral system characteristics and the design of the conversion and energy utilization process. In this context, it was developed a mathematical model to determine the energy efficiency of silvipastoril production system integrated with a cogeneration system for the production of thermal, mechanical and electrical energy. It can be concluded that these results are advantageous in relation to the conventional modalities of energy generation, taking into account the prices of electricity practiced in the market.

Keywords: cogeneration of energy, thermoeconomic analysis, exergoeconomic cost, exergoeconomic efficiency, silvipastoral system, modeling, simulation

1. Introduction

The procedures for the production and use of energy resources are the center of concern in the contemporary world, which requires the establishment of a more harmonious relationship between issues related to climate, energy, the environment and society [1].

According to the bibliographic review made by [2], several studies on future perspectives on the contribution of biomass to the global energy supply have reached very different conclusions. To exemplify, there are studies that indicate projections for the year 2050, below 100 EJ/year, while others, indicate them above 400 EJ/year. The major reason for it is that the parameters used are very uncertain, and subject to widely different opinions.

In any case, biomass of forest origin is a potential renewable resource, which can be planned and used as an energy alternative in view of the need to diversify the energy matrix [3].

According [4], energy is essential for individuals and populations to escape from poverty and move onto a path of greater well-being, security and prosperity. In view of this, a strategy is planned with a view to promoting pathways with the supply of energy to meet basic needs with the promotion of more modern and innovative ways of using biomass to generate income and reduce poverty, a strategy that is associated with other better objectives, such as the management, protection and improvement of productive ecosystems and landscapes, greater the use of sustainable and renewable bioenergy, which will mitigate climate change.

Consistent with the prospects for insertion of forest biomass for a more sustainable future, the silvopastoral system is an agroforestry modality with great potential [3].

According to [4], silvopastoral systems are agroforestry systems characterized by the association of tree crops, pastures and animals, constituting an efficient means of promoting the sustainable use of land.

According to [5], the commercial livestock activity is the main factor of deforestation in the world, with several negative environmental and social impacts.

Forest restoration, on the other hand, can increase soil productivity and fertility [6]. It can also improve the infiltration of water and its preferential drainage flow, since the trees in the pasture system reduce runoff in the face of greater rainfall intensities [7], making the silvopastoral system, a modality of high interest.

Many studies have demonstrated the environmental and economic benefits that can be obtained with the use of silvopastoral systems in agricultural activity.

Among others, we can pontuate [8], that evaluated the impacts of pasture afforestation systems on livestock activity in relation to meat quality.

Other studies have analyzed carbon stocks [9], soil quality [10] and the influence of grazing on the decomposition of tree stumps and roots [11].

In this way, silvopastoral systems have greater biodiversity and offer more environmental services when compared to conventional livestock systems. It can also offer environmental and economic benefits with the addition of a sustainable forest biomass production system and income generation for farmers [12].

Studies also shows that the configuration of tree planting has interactions with the environment, generating impacts on productivity, environmental characteristics and the soil, such as its hydrological properties [13].

In this context, this work aims to develop a mathematical model capable of making the thermoeconomic evaluation of a silvopastoral system for energy purposes.

The proposed simulation model is based on three principles, which are:

1. Mass balance;

2. Energy balance;

3. Thermoeconomic balance;

For the development of the work, cost factors and productive characteristics of silvopastoral systems, appropriate for the region of the Sandstone Caiuá, northwest of the State of Paraná, Brazil, will be considered.

It is noteworthy that the proposed system includes the silvopastoral system associated with a cogeneration process in which the biomass of forest origin is used as raw material. Cogeneration is defined as the production of two forms of energy simultaneously using a single fuel. The most common example is the use of a single thermal source for the production of thermal and electrical (or mechanical) energy.

The specificities and characteristics of the cogeneration system to be used is not part of the present work, it only assesses its efficiency.

1.1 Mass balance

The mass balance is based on the principle of conservation of mass, that is, the amount of mass that enters a process is equal to the amount of mass that comes out of it.

Therefore, as a starting point, it is necessary to quantify the average biomass produced annually by the silvopastoral system for energy purposes.

Thus, the proposed simulation starts from considering the configuration or spatial arrangement of the tree plantation for the silvopastoral system to be evaluated.

A silvopastoral system can consist of different arboreal spatial arrangements. It is a factor of great relevance when it is intended to carry out studies aimed at analysis of silvopastoral systems, since it is directly associated with the productivity of forest biomass, pasture and livestock.

The productivity of forest biomass is the result of many factors and variables, such as its edaphic characteristics, the water regime and soil nutrients, among many others.

However, the avaluation of the biomass productivity as a function of the spacing or arrangement of the trees without changing their density in the occupied area was the object of study by [14]. The authors concluded that the so-called "edge effect" has an influence on the growth of biomass.

The initial density of planting and the characteristics of the tree on growth, wood density and anatomical properties for the forest species were the object of study by [15].

According to the research by [16], it is important to assess the influence of the spatial arrangement of the silvopastoral system with regard to the quantity and quality of light and its effects on the production and chemical composition of the pasture.

This is a productive aspect relevant to livestock activity and compared the effect for a group of spatial arrangements. It was found that the 3.0 m x 2.0 m spacing offered the largest increase in dry matter production, but the denser spacing offered improvements in the composition of forages.

Thus, the spatial arrangement to be evaluated considering rows of trees with a width of 3 m x 2 m according [16], but any other arrangements can be simulated.

A certain area of pasture with the silvopastoral system can be characterized in terms of spatial arrangements, to be used in the mathematical modeling by defining five variables, which are:

1. area (in m^2);
2. distance between ranks, D_r (in m);
3. number of rows of trees in a rank, N_f (units);
4. distance between trees in a row, d_a (in m);
5. distance between rows, d_f (in m)

In our simulations, each species and each productive arrangement can be calculated using the matrix form of the equations. However, the present purpose is to present the fundamental mathematical relationships that are employed.

So, the density (or quantity) of trees in the silvopastoral system, depends on the spatial arrangement of afforestation in the planted area. It varies according to number of rows in a rank, the distances between rows, trees in a row or ranks, according to Eq. (1), expressed in (trees per hectare or trees per area).

$$number\ of\ trees\ in\ an\ area = \frac{N_f\ x\ area\ in\ (m2)}{d_a\ x\ \left(D_r + \left(N_f - 1\right)\ x\ d_f\right)} \tag{1}$$

The average annual volumetric increase in forest biomass, expressed in (m3/(ha. year)), is a statistical data on the average productivity of each forest species referred to a reference silvicultural system for the location or region.

So, the first variable to be considered as a reference in the analysis of the simulation will be the "total gross productivity of forest biomass" harvested in the monoculture system of silviculture with a forest species in a given area under the standard spatial arrangement (3 m x 2 m), at the end of a planting cycle.

So, based on the "total gross productivity of forest biomass", which consists of the final harvest of a known number of trees per hectare in conventional forestry, after a too known number of years, from planting to harvest, it is possible to obtain the average annual gross productivity per cultivated area (tonnes/(ha.year)).

Considering the basic density of dry forest biomass of that species, in (g/cm3) and the humidity factor on a wet basis in (%), we can calculate the average annual volumetric increase in forest biomass, I_{ma}, according to Eq. (2), expressed in (solid m3/(ha.year)).

$$I_{ma} = \frac{biomass\ moisture\ (wetb\%)}{basic\ density\ (g/cm3)}\ x\ \frac{gross\ productivity\ (tonnes)}{time\ planting\ to\ harvest\ (years)} \tag{2}$$

As seen by the studies by [14]. the "edge effect" has an influence on the growth of biomass as a function of the spacing or arrangement of the trees. So, it is possible to predict the establishment of a factor influencing the silvopastoral arrangement, (dimensionless) and the productivity of dry forest biomass, P_{mf}, obtained in a total cultivated área, in (ha), according to Eq. (3), expressed in (tonnes/year).

$$P_{mf} = silvopastoral\ factor\ x\ \frac{number\ of\ trees\ per\ hectare\ in\ the\ silvipastoral\ system}{number\ of\ trees\ per\ hectare\ in\ the\ conventional\ pasture}\ x\ I_{ma}\ x\ basic\ density\ x\ area \tag{3}$$

So, based on the mass balance, it is possible to estimate the average mass rate per forest species, referring to the average hourly flow of forest biomass, B_f, in (kg/h), which depends on the estimated average annual production of biomass, P_{mf} and the annual operating time, in (hours/year), according to Eq. (4), expressed in (kg/hour).

$$B_f = \frac{1000\ x\ annual\ production\ of\ biomass, P_{mf}\ (tonnes/year)}{annual\ operating\ time\ (hour)} \tag{4}$$

1.2 Energy balance

Like the mass balance, the energy balance is based on the principle of energy conservation, that is, energy cannot be created or destroyed, but transformed. Therefore, the energy entering the process must also be equal to the energy leaving it.

To understand the difference in terms of physical and quantitative meanings used in this simulation, it is necessary to explain the difference between energy and exergy.

According [17], to determine energy efficiency or performance in an open system it is necessary to make the mass balance and the energy balance that goes in and out control volume, constituting the thermal balance. However, the thermal balance does not provide the real values, since the full conversion of energy is considered without having to there, energetic destruction.

The exergetic method, however, allows to analyze the quality of the process in which the heat turns to work. Allows you to calculate energy losses, such as capacity carrying out work on the part of heat or steam and discovering its causes.

According to [18], exergy depends on the state of the fluid being considered and the state of the environment present.

According to the author, exergy of a system is defined as the maximum work capacity that can be performed by the compounds of the system in a reference environment. Therefore, exergy is defined as being the maximum possible useful work to be obtained by a flow of energy under conditions imposed by the surrounding environment.

It is also noteworthy that energy is conserved in any system or process. The energy cannot be destroyed, while exergy can be destroyed or lost according to [19].

Exergy incorporates concepts from first and second law of thermodynamics, but in real systems, exergy is never conserved. The analysis of a process or system through simultaneous use of the first and second laws of thermodynamics is, therefore, associated with the concept of exergy, or efficiency, or useful energy. According to [19] is therefore, the exergy and not the energy that can be valued as a merchandise.

So, based on the energy balance, it is possible to estimate the average exergy rate of entry of a process of energy transformation (cogeneration system) on a wet basis of the forest biomass.

The combustion of biomass itself implies the loss of its chemical exergy. Even if the efficiency in the boiler, for example, is high, say 90%, a good part of the exergy is lost in it.

According to [20, 21], the thermal exergy made available to the thermal cycle can be obtained according to the moisture content, the chemical composition contained in the forest biomass and the specific chemical exergy of each type.

A practical difficulty is to know the chemical composition of forest species and the relationship between the chemical exergy of biomass and the exergy effectively released in its complete combustion to be applied in the simulation. Thus, the exergy ratio to be released to the thermal cycle by each forest species used and its superior calorific value, according to the information provided by [22].

The superior and inferior calorific power of dry forest biomass of each forest species are expressed in (*MJ/kg*). They are tabulated and used in the simulation model in the form of a dimensionless exergy relationship for each species of forest biomass on a dry basis, R_{ex}.

An approximate value of R_{ex} is assigned, whenever the inferior calorific power of a given forest species is not available.

So, the rate of average exergy offered by each species of forest biomass on a dry basis at the beginning of the thermal cycle, E_{xibs}, will be given by the Eq. (5), expressed in (MJ/kg).

$$\text{dry } exergy\ IN = rate\ exergy\ x\ upper\ calorific\ value \tag{5}$$

The biomass moisture impacts its exergy and a standardization can be established based on [22], which outlined an experimental curve approximation.

For practical purposes, an equation can be used to estimate the average exergy rate offered by each species of forest biomass on a wet basis at the entrance of the thermal cycle, according to Eq. (6), expressed in (MJ/kg). Humidity factor is the dimensionless relationship between humidity and exergy of each forest species.

$$\text{wet } exergy\ IN = humidity\ factor\ x\ \text{dry } exergy\ IN \tag{6}$$

Therefore, the overall average exergy of the wet cycle thermal input, E_{xibm}, can be obtained based on the specific exergy on a wet basis, according to Eq. (7), expressed in (MJ/kg).

$$\textit{medium}\ \text{wet}\ \textit{exergy IN} = \textit{summation of all wet exergy IN} \tag{7}$$

The effective input power of the cogeneration process, can be calculated by the Eq. (8), expressed in (MW).

$$\textit{input power} = \frac{\textit{medium}\ \text{wet}\ \textit{exergy IN x flow of biomass}, B_f}{3600} \tag{8}$$

The difference between the output power and the input power can be understood as destroyed exergy.

As already mentioned, a considerable part of the loss of exergy in thermal power plants occurs in the boiler and not in condensers, which promote rejection of heat.

Therefore, an efficient energy use project must be planned for the use of the portion of thermal energy, whose utilization rate will depend on the characteristics of this energy use process.

According to [23], cogeneration may have better energy efficiency when compared to conventional energy conversion, since the thermal energy produced is underutilized or can be best used.

Thus, two concepts of exergetic efficiency can be defined, the efficiency of the cogeneration system, η_{COG}, and the efficiency of the electricity generation system, η_{EE}.

Once the energy efficiency of the cogeneration system is known, η_{COG}, the effective output power of the cogeneration process will be given by Eq. (9), expressed in [MW]. It represents the power available primarily in the form of thermal energy with additional capacity to perform mechanical work

$$\textit{output power} = \eta_{COG}\ \textit{x input power} \tag{9}$$

In the same way, we can calculate the active power of the electricity generation, in [MW], also as a function of the input power according to Eq. (10).

$$\textit{electricity active power} = \eta_{EE}\ \textit{x input power} \tag{10}$$

Therefore, the available power of thermal generation with possibilities of use can be obtained by the Eq. (11), expressed in [MW].

$$\textit{available thermal power} = \textit{output power} - \textit{electricity active power} \tag{11}$$

The output power, in turn, can be understood as having three components, which would be:

1. Thermal losses;

2. Usable thermal exergy (or useful thermal exergy);

3. Usable kinetic exergy (in mechanical movement);

According [24], exergy may be associated with work or heat transfer. In the cogeneration system, kinetic exergy is associated with work transfer and thermal exergy is associated with heat transfer.

The kinetic exergy portion can be almost entirely converted into electrical energy, since its conversion efficiency is close to 100%, saved by reduced losses of exergy from a flow of mechanical energy (rotor of a generator in movement) that is converted into electrical energy, [23].

The power conversion rate at the input exergy to electricity is generally not much higher than 1/3 (it is, $\eta_{EEmax} \cong 33\%$).

However, the same does not happen from the point of view of temperature, that is, of thermal energy, on which it must be considered that the exergy of a thermal flow must be calculated according to the variation of the water temperature in relation to the environment, going from an initial temperature to a final temperature, in [Kelvin], according to what [23] called "temperature factor exergetic", according to Eq. (12), expressed in [%].

$$temperature\ factor\ exergetic = 1 - \frac{initial\ temperature}{final\ temperature} \tag{12}$$

Still according to [23], the temperature factor exergetic must be multiplied by the available thermal power produced from the outlet to obtain the useful thermal exergy flow (or useful thermal power), according to Eq. (13), expressed in [MW].

$$useful\ thermal\ power = temperature\ \text{factor exergetic}\ x\ available\ thermal\ power \tag{13}$$

Eq. (14) calculates the useful output power, expressed in [MW]

$$useful\ output\ power = electricity\ active\ power + useful\ thermal\ power \tag{14}$$

As the output and input powers refer to the annual average, the relationship between these corresponds to the overall exergetic efficiency of the cogeneration system, corresponding to the same relationship between the useful annual average exergy estimates, according to Eq. (15).

$$exergetic\ efficciency = \frac{useful\ output\ power}{input\ power} \tag{15}$$

The electrical power generated will be considered equal to the average power or guaranteed by the thermoelectric plant. Assured power is defined as the maximum power that a plant can supply during its worst cycle of raw material availability (fuel or primary energy).

The installed power or nominal power of the thermoelectric plant must be greater than the effective power of electricity generation. The capacity factor, is the relationship between the annual electricity supplied and the product of the installed power over time of annual operation.

This means that a plant that operates at full load full time, without operational intermittence, it will have the unit capacity factor.

In practice, the generation capacity factor is always less than the unit, the average of the generation factor being thermoelectricity capacity equal to 0.55 [25].

So, the nominal power of the electric generator of the thermoelectric can be dimensioned based on the Eq. (16), expressed in [MW].

$$nominal\ power\ of\ the\ generator = \frac{electricity\ active\ power}{load\ factor} \tag{16}$$

Thus, it is possible to estimate the average useful annual exergy generated in this process, which will be the integration of both types of average powers (thermal and electrical) developed over time (in hours) of the year, according to Eq. (17), expressed in [MWh/year].

$$useful\ annual\ exergy = useful\ output\ power\ x\ annual\ operating\ time \qquad (17)$$

1.3 Termoeconomic balance

Thermoeconomy deals with the relationship between the thermal efficiency of the processes of conversion and energy use and the costs of investments and operation of these processes.

The central objective of thermoeconomics is to seek maximum thermal efficiency associated with the lowest economic cost, as long as they are adequately met with the requirements of operational reliability, thermodynamic restrictions, etc.

As pointed out by [18], the word thermoeconomics would be ambiguous, since it could refer to conventional energy analysis under the concept of the first Law of Thermodynamics, which does not consider the irreversibilities existing in all real energy conversion processes. In view of this, he proposed the use of the term exergoeconomics for analysis based on exergy under the concept of the second Law of Thermodynamics. The origin of the word comes from the Greek "ex" and "ergo", meaning "extraction of labor" and economics.

In the proposed simulation model, the thermoeconomic balance of the process has the objective to estimate the exergoeconomic efficiency of the cogeneration system from biomass forest produced by the silvopastoral system.

The associated costs are grouped into two categories: fixed costs and variable costs, when added together, make up the total costs of the process, according to Eq. (18), expressed in [$/year].

$$fixed\ costs = summation\ of\ all\ fixed\ costs\ to\ produce\ electric\ and\ thermal\ energy \qquad (18)$$

The fixed costs for the production of electricity are dependent on the following variables that impact on fixed costs, which are:

1. average annual cost due to Operation and Maintenance (O & M) activities in function of the installed capacity for electric energy generation in cogeneration, C_{fgEE}, expressed in (\$/(kW.year));

2. the nominal power of the generation (installed power), P_n, expressed in (MW);

3. average annual cost of investment in the cogeneration system for electricity generation, C_{iEE}, expressed in (\$/year);

The fixed costs for the production of electric energy can be estimated by the Eq. (19).

$$C_{fEE} = C_{fgEE}\ x\ P_n + C_{iEE} \qquad (19)$$

Similarly, the fixed costs for the production of thermal energy are dependent on the following variables that impact on fixed costs, which are:

1. average annual cost due to Operation and Maintenance (O & M) activities in function of the installed capacity for electric energy generation in cogeneration, C_{fgH}, expressed in (\$/(kW.year));

2. the useful thermal power, expressed in (MW);

3. average annual cost of investment in the cogeneration system for useful thermal energyC_{iH}, expressed in (\$/year);

The fixed costs for the production of useful thermal energy can be estimated by the Eq. (20).

$$C_{fH} = C_{fgH}\ x\ useful\ thermal\ power + C_{iH} \tag{20}$$

The average annual cost related to the portion of investment in generation of electrical energy, C_{iEE}, and thermal energy, C_{iH}, expressed in (1000\$/year), as a function of average investment in installed capacity for the generation of electricity (and thermal energy) in a cogeneration system, in (1000\$/year) and of the installed generation (nominal power of the generation or useful thermal energy), in (MW) and the depreciation time of the investment, T_{di}, in (years).

The average annual cost of investment in generation of electrical energy is estimated according Eq. (21) and (thermal energy), according to Eq. (22).

$$C_{iEE} = \frac{investment\ in\ installed\ capacity\ x\ P_n}{T_{di}} \tag{21}$$

$$C_{iH} = \frac{investment\ in\ thermal\ capacity\ x\ useful\ thermal\ power}{T_{di}} \tag{22}$$

Variable costs are composed of the sum of the costs of cogeneration of energy (electric and thermal), cost of transport and cost of forest biomass, according to Eq. (23).

$$variable\ costs = summation\ costs\ (cogeneration\ energy, transport\ and\ forest\ biomass) \tag{23}$$

The average annual variable costs for the generation of electrical and thermal energy cogeneration process, can be calculated, in [\$/year], by Eqs. (24) and (25).

$$\begin{gathered} costs\ of\ cogeneration\ electrical\ energy = \\ electrical\ generation\ variable\ cost\ x\ annual\ electrical\ exergy \end{gathered} \tag{24}$$

$$\begin{gathered} costs\ of\ cogeneration\ thermal\ energy = \\ thermal\ generation\ variable\ cost\ x\ annual\ thermal\ exergy \end{gathered} \tag{25}$$

The cost of transporting forest biomass depends on the average transport distance, in [km], the average transport cost, in [\$/km] and the volume of the total load to be transported, P_{vf}, in [m3/year].

To estimate the total volume of the load to be transported, it will be necessary to consider previously calculated data about the average annual productivity of forest biomass and convert it into volumetric terms (m3/year), according Eq. (26),

$$volumetric\ forest\ biomass, P_{vf} = \frac{productivity\ of\ forest\ biomass, P_{mf}}{basic\ density\ \left[\frac{g}{cm3}\right]} \tag{26}$$

So, the cost of transporting can be calculated, in [$/year], by Eq. (27).

$$transport\ cost = av.distance\ x\ av.transport\ cost\ x\ volumetric\ forest\ biomass \quad (27)$$

The cost of forest biomass is the sum of the total average annual cost of forest management by the silvopastoral system (or cost of biomass production in the silvopastoral system), with the average annual cost of remuneration for the use of pasture land, according Eq. (28), in [$/year].

$$cost\ of\ forest\ biomass = summation\ costs\ (management\ and\ remuneration\ land) \quad (28)$$

The cost of biomass production in the silvopastoral system (or management cost), in [$/year], depends on the planted area, in [hectare] and the cost of production of forest biomass (which is a statistic data of silvicultural activity), in [$/(hectare.year)]. The sum of the planted area is the total area multiplied by the relationship between the density of trees in the silvopastoral system and the density of trees in the monocultural reference system (with the same species).

So, the cost of biomass production can be calculated by Eq. (29).

$$\begin{gathered} management\ cost, C_{pfs} = \\ cost\ of\ production\ of\ forest\ biomass, C_{pf}\ x \\ summation\ of\ the\ planted\ area\ in\ the\ silvipastoral\ system \end{gathered} \quad (29)$$

The equation referring to the cost of remuneration for land use depends on the silvopastoral arrangement, the value of the land lease practiced in the region and the planted area, in [$/(hectare.year)], according to Eq. (30), expressed in [$/year].

$$\begin{gathered} remuneration\ land\ cost, C_{rem} = remuneration\ land\ per\ area\ x \\ summation\ of\ the\ planted\ area\ in\ the\ silvipastoral\ system \end{gathered} \quad (30)$$

Finally, the total cost of the integrated forest biomass production system with the energy cogeneration system, will be the sum of fixed and variable costs, according to the Eq. (31), expressed in [$/year].

$$total\ cost = summation\ of\ fixed\ costs\ and\ variable\ costs \quad (31)$$

According to [18], one of the objectives that can be obtained with exergoeconomic analysis is to calculate the costs associated with manufactured products.

In the present study, the product is the useful energy in thermal and electrical forms and its global exergoeconomic cost is determined by the Eq. (32), expressed in [kWh/$].

$$exergoeconomic\ cost = \frac{useful\ annual\ exergy}{total\ cost} \quad (32)$$

The exergoeconomic cost is an important indicator for the analysis of the economic viability of this unconventional modality of energy use.

2. Methodology and simulations

As mentioned, the present work proposes to evaluate the viability of an unconventional energy alternative by means of a mathematical simulation system.

It is the possibility of using silvopastoral systems for the production of forest biomass to be used as fuel (raw material) in an energy cogeneration system.

With this intention, a mathematical model was developed capable of evaluating the thermoeconomic viability of the system proposed.

The analysis procedure to be used in this work will be to evaluate the case studies that will be considered, in order to test and evaluate the effectiveness of the simulation model equations for which it was proposed.

2.1 Mass balance

The simulation model used in this work, evaluates the productive data from real cases. According [26], in terms of planted forests, the predominant genus in Brazil is the Eucalyptus, which had in 2015 a total area of 7.8 million hectares planted, where the main cultivated species indicated for the tropical and subtropical climates are, among others (Eucalyptus): camaldulensis, cloeziana, dunnii, grandis, saligna, tereticornis, urophylla, benthamii and the hybrid Urograndis (urophylla x grandis). *Eucalyptus grandis* is the most common, with almost 50% of the total area, followed by saligna and urophylla.

Therefore, for the purposes of the simulations that follow, these species (sp1, sp2, sp3) are considered with their typical characteristics and productive data, although it can apply to any other species.

In order to prospect perspectives on productive data in terms of forest biomass, with the silvopastoral system in the same local conditions, case studies are assumed in **Tables 1–4**. The data considered are compatible with those practiced in the evaluated region.

Several different situations regarding productive data can be assessed. In one of these case studies, the total gross productivity of the forest biomass (on a wet basis) was obtained, after 7 years from planting to harvest: 678 tons per “alqueire paulista”, which is a measure of a very common area in Brazil and corresponds to 24200 m2.

It means that, the average productivity per hectare obtained after seven years was, 280.1 (tonnes/hectare).

The data referring to the spatial arrangements and productivity of forest biomass to be evaluated are real practices productive data of the region under evaluation.

Distance between trees	Distance between ranks	Distance between rows	Number of rows	Tree density (trees / hectare)
da (m)	**Dr (m)**	**df (m)**	**Nf (un)**	**Na (un)**
2	18	0	1	277,8
2	18	3	2	476,2
2,5	18	2,5	3	521,7
1,7	18	3	2	560,2
2	21	0	1	238,1
2,5	25	3	3	387,1
2,5	21	3	2	333,3
2	30	3	2	303,0
2,5	30	2,5	3	342,9

Table 1.
Data and results estimated by Eq. (1).

Forest species	Biomass moisture[2]	Average basic density of forest biomass[3]	Gross productivity of forest biomass	Time planting to harvest	Average annual volumetric increase in forest biomass
	(%)	(g/cm^3)	(tonnes/ hectare)	(years)	(m^3/(ha.year))
sp1	27,50	0,479	225	7	48,7
sp2	27,50	0,465	225	7	50,1
sp3	27,50	0,559	225	7	41,7
not specified[1]	30	0,50	517,6	20	36,2
Grevillea robusta[1]	25	0,6	125	7	22,3

[1]*Real cases.*
[2]*Wet basis in [%]. Refers to: one minus the average humidity measurement of forest biomass after post-harvest drying in the ambient condition (Humidity on a humid basis).*
[3]*Data source: [27].*

Table 2.
Data and results estimated by Eq. (2).

Silvopastoral Factor[1]	Number of trees per hectare in the silvipastoral system	Average annual volumetric increase in forest biomass	Average basic density of forest biomass (g/cm^3)	Cultivated area	Annual production of biomass
(dimension less)	Na (trees/ hectare)	(m^3/(hectare. year))	(g/cm^3)	(hectare)	(tonnes/ year)
1,2[2]	476,2	45,7	0,52	5,0	41
1,1[2]	476,2	45,7	0,52	5,0	37,4
1,3[2]	476,2	45,7	0,52	5,0	44
1,2[3]	333,3	45,7	0,52	5,0	28,5
1,2[3]	277,8	45,7	0,52	5,0	24

[1]*Silvopastoral factor: assigned value.*
[2]*Note 1: The objective of the three first line, is to assess the effect of the influence of the silvopastoral factor.*
[3]*Note 2: The objective of the fourth and fifth line, is to assess the effect of the influence of the density of trees per hectare and the spatial arrangement.*

Table 3.
Data and results estimated by Eq. (3).

Forest species[1]	Cultivated area (hectare)	Annual production of biomass (tonnes/year)	Average flow of forest biomass (kg/hour)[2]
sp1	150.0	1,198.9	136.9
sp2	120.0	959	109.5
sp3	80.0	639.6	73.0
summation:		2,797.5	319.4

[1]*The same genetic species as before (and the same basic density and average productivity); number of trees per hectare in the silvopastoral system: 476.2 (trees/hectare) with spatial arrangement: 18 m x 2 m x 3 m and silvopastoral factor: 1.2.*
[2]*Annual operating time considered: 8760 hour/year.*

Table 4.
Data and results estimated by Eqs. (1)–(4).

Table 1 shows and calculate the tree densities, according to Eq. (1), of some of the possible spatial arrangements that are commonly practiced in silvopastoral systems in the evaluated region.

Based on data on gross productivity in some areas, **Table 2** calculates the average annual volumetric increase in forest biomass.

Thus, according to Eq. (4), it is possible to estimate the average annual hourly flow of forest biomass, considering the annual time of operation of the energy conversion process, for each case study evaluated in **Tables 1–3**.

2.2 Energy balance

The energy balance applies to the energy conversion process. From the input data, Eqs. (5)–(8) calculate the input exergy on a dry and wet basis for each species of forest biomass and the average exergy.

Eqs. (4) and (5) are used to estimate the exergy provided by each forest species, as shown in **Table 5**, each with its exergy rate value, superior calorific value and humidity factor.

Although the forest species in **Table 5** are presented in a generic way, the magnitudes attributed are compatible with those of common species in the region.

In order to simulate the average exergy of entry into the cogeneration system, **Table 6** considers the same hypothetical data as the previous flow of forest biomass.

The mathematical resource for calculating species diversity is the use of matrix variables of the order 1 x n, where n is the number of forest species present in the process.

As long as the energy efficiency of the cogeneration process and the conversion to kinetic energy are known, Eqs. (9)–(11) make it possible to calculate the output powers available in the forms of electrical (or mechanical) and thermal energy, according to the data exemplified previously, shown in **Table 7**.

The exergetic temperature factor, according to [23], can be calculated as a function of the temperature variation. So, considering that the use of available

Forest species[1]	Exergy rate	Superior calorific power (MJ/kg)	Humidity factor	Dry exergy IN (MJ/kg)	Wet exergy IN (MJ/kg)
sp1	0.925	19.46	0.70	18.00	12.60
sp2	0.900	19.67	0.75	18.19	13.64
sp3	0.850	19.46	0.80	16.54	13.23

[1]*Assigned quantities are compatible with those of common species in the region.*

Table 5.
Data and results estimated by Eqs.(5) and (6).

Forest species	Flow of forest biomass (kg/hour)	Wet exergy IN (MJ/kg)	Specific wet exergy IN (MJ/kg)	Average exergy IN	Input power (MW)
sp1	136.87	12.26	1677.98		5.71
sp2	109.46	13.65	1494.16		5.67
sp3	73.02	13.23	966.03		3.55
summation:	319.35		4138.16	12.96	14.90

Table 6.
Data and results estimated by Eqs. (7), (8).

Input power	Cogeneration system efficiency	Output power	Kinetic energy conversion efficiency	Active power of the electricity generation	Available thermal power
(MW)	(%)	(MW)	(%)	(MW)	(MW)
14,90	65	9,68	30	4,47	5,21

Table 7.
Data and results estimated by Eqs. (9)–(11).

thermal energy aims to heat water from initial to final temperature, **Table 8** estimates the values for some case studies from the data previously exemplified, according to Eqs. (12)–(15).

To finalize the analysis of the energy balance, **Table 9** according to Eqs. (16) and (17) presents useful data for the estimation of the average annual flow of useful energy and for the dimensioning of the nominal generator power for the generation of electricity.

It was seen that the economic costs of the process are grouped into two categories: fixed costs and variable costs. **Table 10**, according to Eqs. (18)–(22) estimates the fixed cost of the process.

It can be seen that from **Tables 10–16**, in the columns on the left are the values considered for the variables and on the right the results obtained.

To assess the average annual variable cost for the production of electrical and thermal energy, it is necessary to define and consider a set of service cost conditions

Case Study	Start/end temperature	Temperature factor exergetic	Useful thermal power	Useful output power	Exergetic efficiency
	(K)	(%)	(MW)	(MW)	(%)
(1)	300/373	19,6%	1,02	5,49	36,8%
(2)	300/500	40,0%	2,09	6,55	44,0%
(3)	300/1000	70,0%	3,65	8,12	54,5%
(4)	300/1200	75,0%	3,91	8,38	56,3%

(1): Energy use with the variation of the ambient temperature up to 100°C.
(2): Energy use with the variation of the ambient temperature up to 227°C.
(3): Energy use with the variation of the ambient temperature up to 727°C.
(4): Energy use with the variation of the ambient temperature up to 927°C.

Table 8.
Data and results estimated by Eqs. (12)–(15).

Load factor[1]	Nominal power of the generator[2]	Useful annual exergy[3]		
		Thermal	Electric	Total
	(MW)	(GWh/year)		
0,55	8,13	34,25	73,40	107,65

[1]*Load factor for thermoelectricity, according to [25].*
[2]*Nominal power of the generator considering active power of 4.47 MW electricity generation, according to Eq. (16).*
[3]*annual useful exergy considering full-time operating (8760 hours/year); thermal energy required for heating water from 300 K to 1200 K (3.91 MW) and active electric output power of 8,38 MW.*

Table 9.
Data and results estimated by Eqs. (16) and (17).

Variables	Values considered	Units	Variables	Values obtained	Units
CfgEE	25,00	($/(kW.year))	CiEE[2]	447,15	(1000 $/kW)
CfgH	25,00	($/(kW.year))	CiH[3]	48,88	(1000 $/kW)
CigEE	1,10	(1000 $/kW)	CfEE[4]	650,40	(1000 $/kW)
CigH	0,25	(1000 $/kW)	CfH[5]	146,63	(1000 $/kW)
Pn	8,13	(MW)	Cf[6]	797,03	(1000 $/kW)
utp[1]	3,91	(MW)			
Tdi	20	(years)			

[1]*utp: useful thermal power.*
[2]*CiEE: average annual cost of investment in generation of electrical energy, according to Eq. (21).*
[3]*CiH: average annual cost of investment in generation of thermal energy, according to Eq. (22).*
[4]*CfEE: fixed costs for production of electric energy, according to Eq. (19).*
[5]*CfH: fixed costs for production of useful thermal energy, according to Eq. (20).*
[6]*Cf: fixed costs, according to Eq. (18).*

Table 10.
Data and results estimated by Eqs. (18)–(22).

associated with the production process in the silvopastoral system, which are described at the bottom of **Tables 11–16**.

Table 11 estimates the variable cost of forest biomass, according to Eqs. (28)–(30).

Variables	Values considered	Units	Variables	Values obtained	Units
Rem[1]	500,00	($/(ha.year))	Crem[3,5]	50.003,00	($/year)
Cpf[2]	250,00	($/(ha.year))	Cpfs[4,5]	25.001,50	($/year)
			Cbf[6]	75.004,50	($/year)

[1]*Rem: average annual cost for remuneration by land use for silvicultural activity.*
[2]*Cpf: average annual cost for the production of forest biomass by cultivation area in a monocultural silviculture system with a spatial arrangement of 3 m x 2 m.*
[3]*Crem: remuneration land cost, according to Eq. (30).*
[4]*Cpfs: cost of biomass production in the silvopastoral system, according Eq. (29).*
[5]*Note: Cpf and Cpfs apply to a silvopastoral system on 350 hectares with an arboreal spatial arrangement of 18 m x 3 m x 2 m and a monocultural reference arrangement of 3 m x 2 m.*
[6]*Cbf: cost of forest biomass, according Eq. (28).*

Table 11.
Data and results estimated by Eqs. (28)–(30).

Variables	Values considered	Units	Variables	Values obtained	Units
Dmed[1]	40	(km)	Pvf[5]	5.709,18	(m3/year)
Pmf[2]	2.797,5	(tonnes/year)	Ct[6]	57.091,84	($/year)
Ctm[3]	0,25	($/$m^3$. km)			
Dbm[4]	0,490	(g/cm^3)			

[1]*Dmed: average distance from the field to the thermoelectric plant.*
[2]*Pmf refers to the average annual productivity of forest biomass, estimated for a silvopastoral system in 350 hectares with an arboreal spatial arrangement of 18 m x 3 m x 2 m.*
[3]*Ctm: average cost for transporting biomass according to volume and distance.*
[4]*Dbm: average basic density of forest biomass.*
[5]*Pvf: global average annual volumetric productivity of biomass, according Eq. (26).*
[6]*Ct: average annual cost of transporting forest biomass, according Eq. (27).*

Table 12.
Data and results estimated by Eqs. (26) and (27).

Variables	Values considered	Units	Variables	Values obtained	Units
CvgEE[1]	0,90	($/MWh)	CvpEE[5]	66.060,00	($/year)
CvgH[2]	0,55	($/MWh)	CvpH[6]	18.837,50	($/year)
TE[3]	34,25	(GWh/year)			
EE[4]	73,40	(GWh/year)			

[1]*CvgEE: average annual variable cost depending on the generation of electric energy in cogeneration system.*
[2]*CvgH: average annual variable cost depending on the generation of thermal energy in cogeneration system.*
[3]*TE: Thermal useful annual exergy.*
[4]*EE: Annual electricity generated (useful annual electric exergy).*
[5]*CvpEE: average annual variable cost of electricity in the cogeneration system, according Eq. (24).*
[6]*CvpH: average annual variable cost of thermal energy in the cogeneration system, according Eq. (25).*

Table 13.
Data and results estimated by Eqs. (24) and (25).

Variables	Values considered	Units	Variables	Values obtained	Units
Cbf[1]	75.004,50	($/year)	Cv[5]	216.993,84	($/year)
Ct[2]	57.091,84	($/year)			
CvpEE[3]	66.060,00	($/year)			
CvpH[4]	18.837,50	($/year)			

[1]*Cbf: cost of forest biomass, according Eq. (28).*
[2]*Ct: average annual cost of transporting forest biomass, according Eq. (27).*
[3]*CvpEE: average annual variable cost for production of electricity, according Eq. (24).*
[4]*CvpH: average annual variable cost for production of thermal energy, according Eq. (25).*
[5]*Cv: average annual variable cost for production of electrical and thermal energy, according Eq. (23).*

Table 14.
Data and results estimated by Eq. (23).

Variables	Values considered	Units	Variables	Values obtained	Units
Fixed costs[1]	797,03	(1000 $/year)	total cost[3]	1.014,02	(1000 $/year)
Variable cost[2]	216,99	(1000 $/year)			

[1]*According to Eq. (18).*
[2]*According to Eq. (23).*
[3]*According to Eq. (31).*

Table 15.
Data and results estimated by Eq. (31).

Variables	Values considered	Units	Variables	Values obtained	Units
Useful annual exergy[1]	107,65	(GWh/year)	exergoeconomic cost[3]	106,16	(kWh/$)
Total cost[2]	1.014,02	(1000 $/year)			

[1]*According to Eq. (18).*
[2]*According to Eq. (31).*
[3]*According to Eq. (32).*

Table 16.
Data and results estimated by Eq. (32).

Table 12 estimates the variable cost of transporting forest biomass, according to Eqs. (26) and (27).

Table 13 estimates the average annual variable cost of electricity and thermal energy in the cogeneration system, according to Eqs. (24) and (25).

Table 14 estimates the average annual variable cost for production of electrical and thermal energy, according Eq. (23).

Table 15 estimates the total cost of the integrated forest biomass production system with the energy cogeneration system, which consists of the sum of fixed and variable costs, according to Eq. (31).

So, the exergoeconomic cost, is determined by Eq. (32), as shown in **Table 16**,

3. Conclusions

The parameter used in this chapter to assess the feasibility of the proposed agroenergetic alternative is the exergoeconomic cost.

The non-conventional alternative evaluated is the use of a silvopastoral system aimed at the production of forest biomass and its energy utilization in a thermal and electric energy cogeneration system.

The economic feasibility analysis is a cost/benefit analysis, which can be done based on tariff parameters practiced in the energy market.

For that, comparative measures with the values practiced in the energy sector can be used.

Just as an example, a comparison parameter is the value practiced from 2003 onwards for the average electricity supply tariff for the Brazilian electric system for all consumption classes and geographic regions of the country [28], which is (61.40 $/MWh), much higher than the value found in the present simulation (9.42 $/MWh).

Therefore, this study presents indications of good viability for this energy alternative as a possibility, which can be inserted among the renewable energy options in the energy matrix of the future.

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