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Assessment Method of Bioenergy in the Industrial Sector

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Abstract

The industrial sector is one of the major energy consumers and polluters in emerging countries. With the great demand for a maximum reduction of gas emissions that aggravate the increase in Earth temperature, alternative sources of energy are being adapted for use in the industrial sector, such as bioenergy. Along with methodologies that ease implementation and use, several decision-making methods are currently under development to provide industrial managers with better scenario alternatives for the implementation of bioenergetic factors. This work aims to develop a decision-making method for the use and exploitation of bioenergy in Brazil, considering the initial assessment of sustainability and the implementation of technologies that compose the process of electricity generation through bioenergy. Fuzzy logic was used as the model development structure. It was used to analyze three case studies of manufacturing companies. As a result, there is an applicability of the method through government subsidies, regionalization of biomass for energy generation, and efforts in adapting and maintaining equipment for energy conversion with a strong driver of reduction of environmental impacts. This proposal, in addition to being useful for the industrial sector, helps the government sector with the reduction of energy, taking knowledge beyond the university using a new structured method, environmentally conscious, in this emerging area.

Keywords: bioenergy, industrial sector. fuzzy logic, biomass, energy conversion, sustainability

1. Introduction

The United Nations Intergovernmental Panel on Climate Change (IPCC) report (International Panel on Climate Change, 2023) shows that urgent and unprecedented changes are needed to reduce impacts on the environment. The report suggested a temperature threshold of 1.5°C above pre-industrial levels and global greenhouse gas emission pathways in response to global climate change. There are great challenges to national and global decision makers. As discussed at COP 27 (United Nations Climate Change, 2022), a clean, efficient and participatory energy consumption is an important strategy to reduce the impacts of climate change.

Different alternatives of renewable energy sources have been explored to reduce the emission of gases that cause the greenhouse effect. Among alternatives, bioenergy is one of the largest sources of clean energy and promoter of less environmental impacts. According to the International Energy Agency (International Energy Agency, 2022), bioenergy represents approximately 55% of the global energy sector and more than 6% of the global energy supply. Thus, there is potential for change in the global energy transition scenario. In Brazil, bioenergy represents 37% of the consumption of biofuels with a potential to use more than 30 MW of electricity. The USA and Brazil are the two main consumers of bioenergy in the world (Brazilian Energy Research Company, 2021).

Considering the aspect of sustainability, (Jin & Sutherland, 2018) reveal that bioenergy, within its structure, must consider environmental, social, and economic aspects. The environmental advantage is that during electricity generation, it may improve soil carbon sink. Besides (Jin & Sutherland, 2018), other works show that sustainability is an essential criterion to be considered within technical aspects for decision making. (Domac et al., 2005) specifically reported the generation of bioenergy using forest biomass, indicating that the use of specific generation of this type of energy may generate benefits such as regional growth, jobs, and economic development. (Timmons et al., 2007) reported an estimated co-generation of around 165 MW for the city of Massachusetts over a period of five years. (Scarlat & Dallemand, 2011) show that in addition to the innovative aspects of production, socioeconomic aspects for bioenergy should include effective socioeconomic availability, such as control of low wages and child labor. Also Ranjbari et al. (2022) discuss another perspective, revealing that the improvement of sustainability in a robust way is directly related to technical factors during the conversion of different forms of biomass into energy. Many times, a bioenergy system can be beneficial to the environment, to economy, and to society if managed in a sustainable way.

However, due to the physical characteristics of different types of raw biomass, there are major difficulties in competing with other fuels for energy generation, as is the case in the industrial sector. Therefore, in addition to the development aimed at sustainability that fuel may generate, a linked technological development is necessary for a unified decision-making system (Rentizelas & Li, 2016). This is true mainly with biomasses with a high lignocellulosic demand, as is the case of sugarcane (Mariano et al., 2013).

Brazil, one of the largest producers of sugarcane in the world from 2021 to 2022, produced 578,777 tons, with a prospect of reaching 2022 to 2023 with 572.87 tons of sugarcane produced. In view of this scenario, although there is a small fluctuation in production, Brazil is one of the major producers of bioenergy mainly for the transport sector, which corresponds to 32.5% of the final energy consumption in the energy matrix. The industrial sector ranks second, with 32.2% of the final consumption in 2022. However, specifically in the industrial sector, the great use of energy is from Brazilian concessionaires (Brazilian Energy Research Company, 2023). Even though Brazil has a national production of electricity of around 85% from renewable matrices, there are about 30% of loss of all electricity during transmission because it is a continental country. Also, by sectoring the industrial sector, it is verified that, according to the Brazilian Institute of Geography and Statistics (Brazilian Institute of Geography and Statistics, 2021), small and medium-sized companies (SMC) correspond to 85% of the Brazilian industrial sector. There are 1,738,021 companies, of which 1,054,998 are individual micro-entrepreneurs (IME), 571,219 micro-companies (MC) and 111,804 small companies (SC) (Brazilian Institute of Geography and Statisticsa, 2023).

Several works have discussed alternatives for the reduction of energy losses in transmission through the generation of energy close to the consumer sector with a greater demand, such as the industrial sector and consequently reduce some socio-environmental impacts. However, an inherent difficulty is an effective methodology that analyzes not only the implementation but that complements it with concepts related to sustainability beyond technology for an efficient energy conversion with the lowest environmental impact possible. One of the main issues in the development of this category of methodology is data characteristics since data have great uncertainties and inaccuracies; consequently, the proposed methodology must consider these characteristics as a form of absorption. Fuzzy logic is a support methodology with these characteristics because it uses data with uncertainties and inaccuracies, absorbing them for the construction of methodologies. Some works have already begun to carry out works using fuzzy logic alone or in a hybrid way with other decision-making methods for different sectors of the productive system. (Wang et al., 2022) verified the cause and effect relationship of the main bioenergy indicators in the agroindustrial sector using the fuzzy-dematel methodology. (Krisnaningsih et al., 2022) ranked the best projects using the fuzzy-AHP for rice biomass bioenergy indicators. (Ossei-Bremang & Kemausuor, 2021) built a model using fuzzy-topsis and AHP (multi-criteria decision-making method for ranking) so that decision-makers could analyze different types of alternative urban biomass. In a way, there are several possibilities for the development of methodologies in various sectors of society. However, the industrial sector faces great challenges.

However, this work aims to develop a decision-making methodology using fuzzy logic for the use of bioenergy in the industrial sector of Brazil. This will be done through the construction of several scenarios, taking into account aspects of sustainability and as a project of industrial technological development. Both externally, with the main sustainability capabilities that the industry must achieve in society, and internally, in the technological stages of electric energy biogeneration, to which companies must adapt. Thus, there is a general overview of how companies will face external problems and how they will adapt through the technological implementation project. In addition, as a complement to fuzzy logic, the AHP was used to generate weights for the various indicators in the external phase. Thus, these weights are essential to guide the various rules generated by this method.

The analysis of sustainability before the installation of biomass electricity generation can bring several viability aspects, among them:

a) Environmental Viability: Sustainability analysis allows evaluating the environmental impact of the bioenergy generation project. Ensuring that the project is environmentally viable is essential to reduce the risk of damage to the local ecosystem and contribute to environmental preservation

b) Economic Efficiency: Sustainability analysis also considers the economic aspects of the project, including the investment, operation, and maintenance costs of the bioenergy plant

c) Social Impact: The development of a bioenergy generation project can also have social impacts on the local community and the involved workers. Ensuring that the project is socially beneficial contributes to local acceptance and support for the enterprise.

d) Risk Minimization: Sustainability analysis helps identify potential project risks, both environmental and economic, as well as social. By anticipating these risks, it is possible to take preventive or corrective measures to minimize future problems and ensure the continuity of bioenergy generation plant operations.

Therefore, with both phases, it is possible to have a complete understanding of the entire internal structure that companies will face. Additionally, three cases with micro, small, and medium-sized companies were studied to identify the main scenarios that need improvement to structure the use of bioenergy.

In this way, this work goes beyond the development of an easy and agile structure for industrial decision makers to inform themselves on the implementation of industrial bioenergy measures in places where there is a great demand for biomass, mainly of sugarcane. This reduces energy waste through transmission networks. Thus, it complies with the Law no. 10,295 of 2001 (Brazilian Energy Efficiency Law, 2001), which provides for the implementation of energy efficiency measures in the various sectors of civil society. The issues raised by COP 27 (United Nations Climate Change, 2022), discussing ways to reduce the emission of greenhouse gases and rescuing excessive carbon in the soil (COP 27) through emerging socio-environmental impacts, are addressed here.

The remaining of this article is organized as follows. Section 2 describes the methodological proposal. Section 3 proposes the construction of the fuzzy model. Section 4 presents the main implications regarding sustainability and industrial and governmental management. Section 5 presents the main limitations of this work and, finally, section 6 presents the final considerations and future work perspectives.

2. Methodology

In this study, four stages were utilized to achieve the proposed objective, as demonstrated in Figure 1. The first stage involved conducting a literature review to identify relevant indicators. In the second stage, a fuzzy mathematical model was developed to facilitate external decision-making methods. The third stage involved the development of a fuzzy prototype for electricity biogeneration using technologies for the electrical conversion of sugarcane waste. Finally, a case study was presented. As a result, it was possible to establish a decision-making method for the utilization of biomass in industrial energy generation.

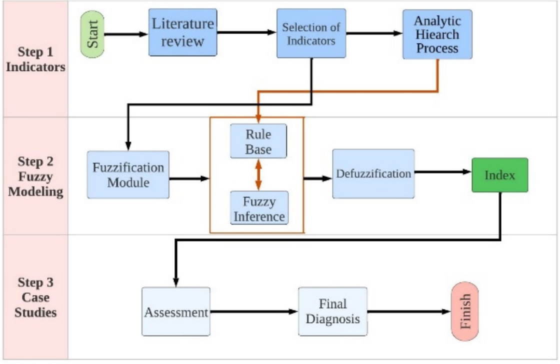

Figure 1. Study structure of the fuzzy model for bioenergy generation

2.1 Selection of Indicators

The literature review was the first step in surveying the indicators used for the development and implementation of fuzzy modeling for bioenergy generation focused on sustainability. The selection of indicators took place through a systematic literature review. Then, the analytic hierarchy process (AHP) was used to generate weights for the arrangement of fuzzy rules (section 3.2). Table 1 shows the indicators and their respective weights.

Table 1. Biomass energy generation model indicators

Social				
Indicator	Abbreviation	Relevance to the model	Weight (%)	Source
Socio-political acceptability	SA	Acceptance of biomass renewable energy technologies by domestic policy makers	50%	(Wang et al., 2022)
Job Creation	JC	Socioeconomic improvement generated by the creation of jobs by companies that dispose of biomass	33%	(Wang et al., 2022)
Social Development	SD	Decreased environmental impact and social improvement through economic improvement and the introduction of bioenergy generating technology	17%	(Wang et al., 2022)
Environment				
Water Use	WS	Impact of water consumption for the generation of bioenergy through agro-industrial waste	50%	(Wang et al., 2022)
Use of Non-renewable Energy	nRE	Impact of the use of non-renewable energy consumed during biomass energy generation. For internal and external transport	50%	(Wang et al., 2022)
Noise Pollution	NP	Impact of socio-environmental quality caused by noise pollution from power generation machines	63%	(Wang et al., 2022)
Land Pollution	LP	Environmental impact on the soil during waste storage	25%	(Aryanpur et al., 2019)
GHG emission	GE	Environmental impact of greenhouse gas reduction through biomass energy transition	12%	(Giuntoli et al., 2016)
Solid Waste Management	SW	Socio-environmental impact by managing solid waste from the industrial process which can be used for bioenergy	44%	(Kheybari et al., 2019)
Liquid Waste Management	LW	Socio-environmental impact by managing liquid waste from the industrial process which can be used for bioenergy	32%	(Kheybari et al., 2019)
Gas Waste Management	GW	Socio-environmental impact of managing gas waste from the industrial process which can be used for bioenergy	24%	(Kheybari et al., 2019)
Economic				
Operation	OP	Cost of adaptation of technological operation for biomass	50%	(Tang et al., 2014)
Energy Consumption Cost	EC	Cost of adapting industrial energy consumption	50%	(Aryanpur et al., 2019)
Subsidies	SB	Government subsidies for industrial bioenergy generation	72%	(Cutz et al., 2016)
Incentives	IC	Capital expenditures related to technological construction	18%	(Aryanpur et al., 2019)
Trade-off	TO	Proportion of the economic benefit obtained in relation to the total cost	10%	(Cutz et al., 2016)

It is important to highlight that the use of AHP is only for indicators at level 1 of Figure 2 (with the exception of social, which is at level 2). In this way, the sum of AHPs is given only in branches; for example, the sum of SW, LW and GW is 100%

2.2 Fuzzy Modeling

In the second step, after surveying indicators, fuzzy modeling was performed.

The Fuzzy Set Theory analyzes sets with imprecise amplitudes considering the pertinence in terms of degree and not true and false (Ross, 2004), which is characteristic of the data Table 1 shows. The fuzzy set, through a curve, can define the degree of relevance, and each point of the output space is mapped in the fuzzy set A, as presented by Equation 1.

$$\mu_A = \chi \rightarrow [0,1] \tag{1}$$

where χ originates from a universal set that is always a classical set and for each x ϵ χ μ_A , verifying the degree of relevance of the element x of χ to the fuzzy set A, with $\mu_A\ (x) = 0$ representing no membership and $\mu_A\ (x) = 1$ representing membership total of x to the fuzzy set x.

The set operations used in this work are those of intersection, following the operator pattern *"and"*, to facilitate access by specialists and following the pattern that indicators have several points of intersection within membership functions. In this way, based on Figure 1, in the construction of the fuzzy model there is a general scheme of a structure of a mathematical model with absorption of uncertainties and inaccuracies.

During "fuzzification," the linguistic variables were elaborated by specialists in the field (Simões & Shaw, 2007). The membership functions used in the development of this model were trapezoidal functions at the extremes and triangular functions at the center. In this way, the calculation managed to trigger several fuzzy functions and exclude those that would not fit this characteristic.

For the elaboration of the rule bases, the description of the relationship of the variables was "If<anterior> and then<consequent>." The antecedent consists of a set of conditions that, when satisfied, even if partially, determine the processing of consequent rules by a fuzzy inference mechanism. When this occurs, it informs that a rule has been triggered (Barros et al., 2017).

To complete the fuzzy modeling, the relationship with the rules, with an inference to implement the subjectivity of data of the development of bioenergy from the biomass in a mathematical evaluation, the standard process of the Mamdani structure was used with the following steps: aggregation, finalization, and composition (Abe, 2000; Barros et al., 2017).

i. Aggregation – consisted of determining the level at which the part (SE) of the rules will be fulfilled using the conjunction (AND), which is represented by the intersection of the operator (MIN);

ii. Conclusion - during the composition, the degree of participation will determine the level of service (DOS), which is the significance of the rule or weight, taking as an example in a domain that varies from 0 to 1, 1 being the highest allowed significance or greater weight;

iii. Composition - represented by the union operator (MAX) that will be used in the condition validation to determine the validity of the conclusion.

Finally, in the mathematical output, the defuzzification, the centroid was used, which consists of a solution of the abscissa at the center of gravity. It is expressed in Equation 2.

$$\mu_{FC\ (x_k\ ,y_k)} = \frac{\sum_{i=1} v_i\ \mu_v\ (\ x_k\ ,y_k\ ,v_i)}{\sum_{i=1} \mu_v\ (\ x_k\ ,y_k\ ,v_i)} \tag{2}$$

Where $\mu_{FC\ (x_k\ ,y_k)}$ is the fuzzification output, $\mu_v\ (\ x_k\ ,y_k\ ,v_i)$ is the aggregate membership function, and $v_i s$ ϵ U is a discrete element of the fuzzy output set.

2.3 Case Study

To conduct the case study questionnaires were sent to some companies in the countryside of the State of São Paulo with the purpose of showing the best use of biomass for energy generation. This region produces a large amount of waste from sugarcane. However, the companies use other resources in the national energy matrix to generate electricity, such as energy from Brazilian concessionaires and coal.

Waste, for the most part, is not used or thrown elsewhere. It is also important to note that, as Brazil is a country of continental dimensions, energy loss during transmission to the receiver is great.

3. Biomass Energy Generation Model

In this section, the steps for biomass energy generation will be presented. The first part will describe the development of the external model for bioenergy generation, and the second part will focus on the internal model of the industry, creating a complete external-internal cycle.

It is important to emphasize that this work adopts a comprehensive perspective of the entire system that comprises both external and internal aspects of industries in biomass electricity generation. A cohesive methodology has been proposed to assess the socio-environmental impact that biomass electricity generation from sugarcane waste can generate. With this in mind, Section 3.1 begins by demonstrating bioenergy through the internal and external sustainability requirements, while Section 3.2 addresses the technological aspect of biomass electricity generation.

3.1 Sustainability Bioenergy Generation

The construction of a composite bioenergy index follows the principle of assessing how a company must overcome challenges to implement a biomass energy generation system, considering aspects of sustainability (economic, environmental, and social). The fuzzy architecture for the bioenergy methodology presented in Figure 2 and is based on multi-level fuzzy aggregations, where input indicators generate other sub-indices until reaching the final aggregation, which will result in the bioenergy index.

The general architecture (Figure 2) has four levels. The first level, input variables, is responsible for the development of level two. The second level, resulting from the indicators, generates economic, environmental and technical data (3rd level), in addition to social input indicators since they are at the second level because they do not have previous ramifications. Thus, the social sub-index is at the 3rd level. The aggregation of economic, environmental and social subindexes is also at the third level, although their composition aims to meet the principles of the (Brundtland, 1987) report (1987). However, as aggregated indicators make up sustainability or not, it is understood that they can be at the 3 level as criteria that meet sustainability.

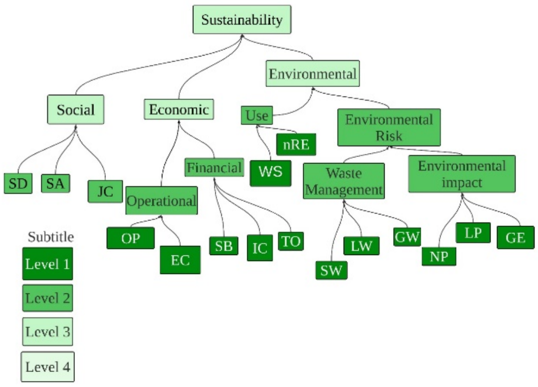

Figure 2. Architecture of the sustainability index

Finally, the fourth level, sustainability and technical, is the composition agents of level 4 (bioenergy index).

Furthermore, it is important to point out that after assigning linguistic terms, trapezoidal functions were used at the ends and triangular functions at the middle (Figure 4). The analysis involving two variables allows establishing a knowledge base with 25 linguistic rules (Supplement A), since five fuzzy sets were used in the input and five fuzzy sets in the output (the fuzzy sets are for the bioenergy index: Terrible Performance (0,0,1,3), Potentially Bad (1,3,5), Acceptable Performance (3,5,7), Potentially Good (5,7,9) and Excellent Performance (7,9,10 ,10), using the Mamdani inference method). The characteristic of the answer followed the if-then criterion (section 3.2), in which specialists gave their answers in order to provide uniformity to the activation of the rules. Finally, the mass center of gravity was used as a defuzzification process. Likewise, the structure determined for level 4 (Figure 2) continued for the previous levels.

For the construction of the bioenergy model, the membership function shown in Figure 3 evidences that it can be standardized to capture the greatest possible number of regions with uncertainties. The trapezoidal functions at the ends capture regions that somehow would not have a need to include these regions.

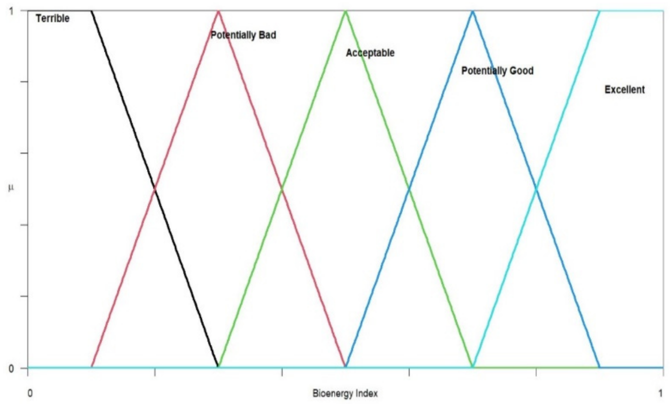

Figure 3. Membership functions for criticality index

That said, the AHP weights (Table 1) weighted the rules through the training algorithm, assigning a class label to the rules shown, IF and THEN, in the defuzzification output. The description of the object occurred as a vector containing the weights of the input indicators at level 1 which were considered relevant for the generation of intermediate indexes at level 2 (Figure 2).

In this way, when selecting the rules in the output for defuzzification through the centroid (Equation 2), the algorithm will autonomously assign a weighting factor according to the weights that specialists treated through the AHP, that is, a rule highlighted in the level 1 as from the social sub-index. The SA x JC x SD rules will be multiplied by 1.5 in the assigned membership functions of SA indicator rules, by 1.33 in the membership functions of the JC indicator rule, and by 1.17 in the membership functions of the SD indicator rules. With this, the entry value at level 2 (Figure 2) will direct the other aggregations of the bioenergy assessment index in the industrial sector.

For the subindexes aggregated with two input indicators (input, use, and operational), the weights have no expression during defuzzification through their membership functions. Since, according to (Saaty & Katz, 1990), the random index for AHPs with 1 or 2 indicators is zero, therefore Table 1 shows equal weights, so that the algorithm will not assign weights differently.

To verify the adequacy of all entries of bioenergy index rules, fictitious data were used with the objective of providing greater amplitude to the rules being activated and, in this way, verifying the functionality of the model. Thus, this study has an adequate quality for the operation of a judicious methodology. After, a classification strip was built with a color palette that represents bioenergy (Figure 4) presenting different scenarios. The hue of green to black means the best to the Terrible point feel (Chatti et al., 2017).

Table 2: Sustainability index rating

Range	Linguistic Word
Very High	[0.85; 1]
High	[0.65; 0.85]
Adequate	[4, 0.65]
Low	[0.15; 0.4]
Very Low	[0; 0.15]

In this way, companies that have achieved the appropriate score can proceed to the electricity implementation phase.

The steps for building the sub-indexes followed the same ones as adopted for the aggregation of levels 3 to level 4 (Figure 2). However, the rules of level 1 and level 2 (social) input indicators were weighted according to the *analytic hierarchy process*, as Table 1 shows.

The sustainability indicators stress the characteristic that a company must face in order to have a complete structure that has the constitution of bioenergy in its resources.

In the environmental aspect, several categories were related to the production of biofuels, which, in a way, have a positive and a negative impact because it is an environmentally correct aspect. These impacts are described in the formation of rules, for example the use of non-renewable energy (nRE), which has a negative impact, and the consumption of water (WS), which has a positive impact, the nRE followed the disposition of the smallest the best and WS followed the rule that bigger is better. The generation of some sub-indexes for the economic aspect followed the same trend as the environmental indicator. Unlike the social indicator, the three input indicators are positive; thus, they followed the trend of the higher the better.

This provides a framework for assessing not only the sustainability scenario, but also the different dimensions separately (social, economic, and environmental). These hybrid approaches play a special role because they manage to provide an overview of the main points that can be tackled for the installation of a dynamic structure for the generation of bioenergy.

3.2 Biomass Power Generation

After developing the model from Section 3.1, the biomass power generation model was created. To generate electricity, several steps must be followed for the conversion of biomass into electrical energy. Starting from obtaining biomass to distributing electric energy in industries, a total of 6 stages are carried out. These steps are illustrated in Figure 4.

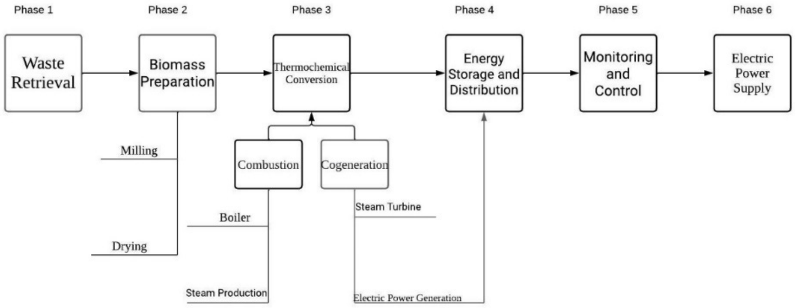

Figure 4. General scheme of biomass electricity generation

It is important to highlight that from the second phase (Figure 4) onwards, the fuzzifications began through branching, equivalent to Figure 2. As a result, the architecture of phase 2 is shown in Figure 5.

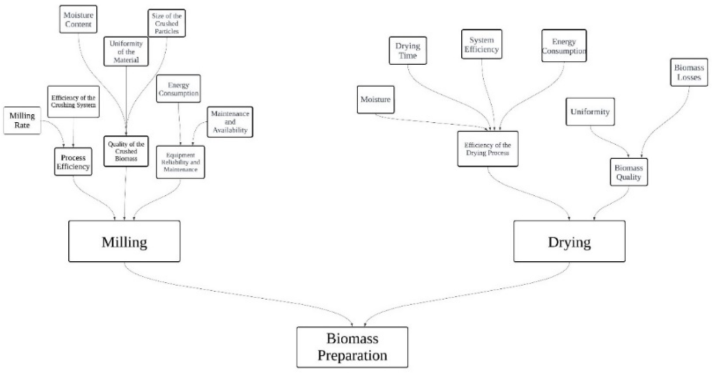

Figure 5. Biomass preparation architecture

The development of fuzzy machinery occurred in the same way as described in the previous section, but without the AHP weights as rule weighting factors for the current model. In Supplement B, you can find the indicators that make up the rest of the model developed following the flow of Figure 6. Additionally, just like in phase 1, there was no fuzzification process in phase 6, as the biomass had already been converted into electricity, requiring only distribution to be carried out.

With this, a scoring range was generated for each phase. In this way, the energy manager evaluated the points where the flowchart needed improvement to function properly. It is important to highlight that, for this implementation phase of the evaluation, there is no need to assess the harmonious functioning of the entire electricity biogeneration system, but it is crucial to evaluate each technology separately.

In phase 3, regarding the generation of electricity through thermochemical cogeneration, the indicator is directly aligned with phase 4, which involves energy storage and distribution. However, it also contributes to phase 3 to ensure the continued operation of the other technologies within this stage.

Table 3: Electricity generation index

Range	Linguistic Word
Very High	[8.5; 10]
High	[6.3; 8.5]
Adequate	[4.5, 6.3]
Low	[1.8; 4.5]
Very Low	[0; 1.8]

3.2.1 Case Studies

This section presents the proposed methodology through case studies. In this way, it can guide the three participating companies. It then shows which actions companies can adopt to implement energy from biomass, with a more in-depth demonstration in each company. The companies are located in a large center, which has an amount of biomass, and most of the time it is not reused for energy generation in sectors with high energy consumption, such as the industrial sector, generating a great socio-environmental impact on the soil and consequently causing an imminent environmental liability.

Due to its exploratory character, the case study method was chosen to analyze the companies. The in-depth study of a small number of companies is especially suited to add depth to research analyses.

Thus, with the data collected, the index for the implementation of bioenergy was delivered to the industrial managers of these companies as forms indicating the characteristics of the social, economic, environmental, and technological indicators (Table 1) using questions that stood out through of linguistic variables, whose purpose is to be an easy and agile method for the implementation of industrial bioenergy.

After collecting data from the input indicators (level 1 in Figure 2), the developed algorithm generated the value corresponding to levels 2 and 3, and thus level 4 could be generated. In this way, through the generated diagnostic analysis, it is possible to build several scenarios from the terrible point to the excellent point (Table 2). Industrial managers will have to overcome them to implement bioenergy in these three industries considering the criteria related to sustainability and technology.

The purpose is to have an easy and agile method for the implementation of industrial bioenergy which exerts the minimum socio-environmental impact in the region. Still, it is important to highlight that this methodology is not restricted to this region alone. It presents a diagnostic scenario for the global implementation of the industrial energy transition.

In the three subsequent cases, the scores of bioenergy indexes and the technological and sustainability indexes (economic, environmental, and social) were presented. Next, the main indicators that need to be adequate for an adaptation to the energy transition focused on the creation of bioenergy.

After completing the study of Model 1, the process of converting bioenergy into electricity should begin, considering aspects of both external and internal sustainability of the industry. In this way, the case studies did not address Model 2 using real data but only conducted a simulation with managers from the top-ranked industries in Model 1 to identify areas where the industry's needs should be better adapted through questionnaires.

Similar to Model 1, Model 2 weighted the key points that industries will need to overcome to implement the methodology successfully.

3.3 Sustainability Index of Bioenergy

3.3.1 Company A

Company A is from the machinery sector. It has about 100 employees and, according to the classification of the Brazilian Institute of Research and Statistics, it is considered a medium-sized company. It emits some waste classified as chips and disposes of them for reuse, uses water for internal cleaning, and is implementing measures to reduce energy consumption.

The environmental manager responsible for power generation filled out the form, and the answers were delivered, normalized and arranged in the developed algorithm. Thus, Figure 6 shows the energy adaptation of company A, which is considered acceptable according to the index shown in Figure 4.

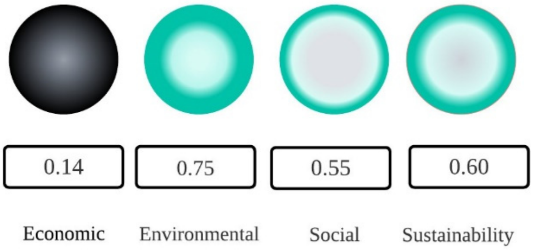

Figure 6: Sustainability index for Bioenergy of the Company A

The economic indicators are the main factors responsible for the downgrading its grade. In this way, the indicators that the company will have to improve are the five economic ones (OP, EC, SB, IC and TO). Table 4 shows the initial score values of the Terrible indicators for the economic sub-index.

Table 4: Indicators for improvement of Company A

Indicator	Score
Operation	0.2
Energy Consumption Cost	0.1
Subsidies	0.03
Incentives	0.25
Trade-off	0.02

Necessarily, as this is a company whose characteristic is to use utility energy for its operation, mainly economic and technological issues are responsible for the implementation of measures for energy consumption through biomass.

From a sustainability perspective, although it is deemed acceptable (score 0.6), the adaptation occurs primarily through economic indicators (score 0.14), which are closely related to technological aspects on a cross-sectional basis. From an economic standpoint, the key indicators involve subsidies as resources are thoughtfully allocated to ensure the effectiveness of sustainable technologies. Additionally, trade-off analysis is employed to ensure that the implementation of energy technologies aligns with the company’s sustainability objectives.

3.3.2 Company B

Company B is in the turning business. It has about 50 employees, that is, a small company. It does not emit waste and has no plan to reduce energy consumption.

In the same way as company A, the environmental manager of company B filled out the forms to create the database for generating the indexes that Figure 7 shows, evidencing how the classification range in Figure 4 was constructed, with a score considered good (0.65).

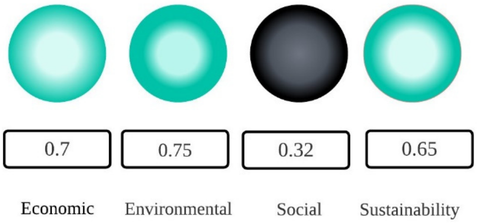

Figure 7. Sustainability index for Bioenergy of the Company B

Company B has a bioenergy index considered good. The main aspect that can be improved and that will leverage the sustainability of the final bioenergy index is the social aspect. The job creation and social development indicators score the lowest and consequently need to be improved. It is important to highlight, as Figure 2 shows, that the entry indicators are at the second level in fuzzy aggregations. Thus, it has a strong influence on the decisions of others since there was no other defuzzification that could make the results more fluid. Table 5 shows which are the main indicators that Company B needs to adequate in order to improve its bioenergy consumption.

Table 5. Indicators for improvement of Company B

Indicator	Score
Socio-Political Acceptability	0.2
Job Creation	0.42
Social Development	0.38

3.3.3 Company C

Company C is from the paper and packaging sector. It has about ten employees, emits plastic waste, and uses water for reuse. It also has plans to improve energy consumption.

Finally, the environmental engineer from company c filled out the form and input data level 1, generating the scenario shown in Figure 8 considering all the aspects that make up the bioenergy index.

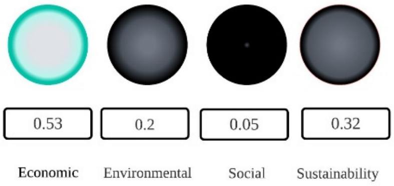

Figure 8. Sustainability index for Bioenergy of the Company C

The company shows (Figure 8) that all indicators that have a social and environmental aspect have a very bad indication, actively influencing the bioenergy indicator, which fits into the acceptable category, much as a result of the technological sub-index. The scenarios show great concern. This is because the industry manager states that the company implements measures to reduce energy consumption, even if it is not of bioenergetic origin. Table 5 shows the main points that the company must improve to adapt to sustainable bioenergy.

Table 6. Indicators for improvement of Company C

Indicator	Score
Socio-Political Acceptability	0
Job Creation	0.2
Social Development	0.15
Noise Pollution	0.37
Land Pollution	0.08
GHG emission	0.14
Solid Waste Management	0.17
Liquid Waste Management	0.33
Gas Waste Management	0.03

As it is a micro-enterprise, its structure is still poor and it needs to develop an adequate structure to reduce energy consumption and consequently manage to implement sustainability as a source of industrial operation to some extent.

Considering the socio-environmental aspects, it is still incipient as there is no program or room for improvements. This is mainly due to the external impacts on the company, as there is no vision for improvement in the external community, given that the water reuse program presented by the company is not suitable for bioenergy generation. For reuse, the company needs to restructure the entire dynamics of environmental indicators.

3.4 Biomass Electricity Generation Project

After the initial phase, the process of implementing electricity generation in the internal power plants of the companies begins. The proposed approach, both externally to the industry and in terms of self-generation of electricity, aims to give appropriate disposal to the region's waste through an energy-saving process from utilities highlighted in section 4.1.

In Figure 4, it is emphasized that biomass needs to undergo an initial pre-treatment process to ensure that the used waste does not generate physical and chemical emissions into the environment, in order to achieve dynamization. This dynamic, besides promoting social sustainability, enables the economic and environmental uniformity of this project.

Considering that Companies A and B have suitable scores to initiate the project, we shaped a database according to the requirements that the managers of Industries A and B dynamically specified as the initial prerequisites for implementation. Thus, the modeling for the specific steps that the industry should adapt to more effectively began.

It was considered that Figure 4 follows a flow for biogeneration of electricity, but for the installation of the internal power plant, the equipment and dynamics can be autonomously designed to generate the final product, which is electricity, in a unique way. As a result, the scoring proceeded as follows. For Phase 2, the scores are presented in Table 7.

Table 7. Indicators for improvement for Phase 2

Biomass Preparation	Company A	Company B
Milling	8	7.7
Drying	9	8.3

The indicator that be must suitable is the grading unit. For Phase 3, Table 8 indicates the scores for the output indicators.

Table 8. Indicators for improvement for Phase 3

Thermochemical Conversion	Company A	Company B
Boiler	6	4
Steam Production	5	3
Steam Turbine	6	2
Electricity Generation	7	1

The indicators to be improved are the boiler efficiency and steam production rate. Additionally, it is important to highlight that while the boiler indicators focus on biomass combustion efficiency and high-quality steam production, the steam production indicators are more oriented towards the performance of the steam turbine and electricity generation from the generated steam. Both sets of indicators are crucial for the assessment and optimization of the biomass electricity generation process, ensuring the efficiency and reliability of the system.

In Tables 9 and 10, you can find the indicators that compose the distribution of electrical energy and the monitoring and control of the generated energy.

Table 9. Indicators for improvement for Phase 4

Electric Power Distribution	Company A	Company B
Distribution to the grid	2	4

Table 10. Indicators for improvement for Phase 5

Monitoring and Control	Company A	Company B
Automation	2	3.2

In Company A, only the indicator "reliability of energy supply" (score 9) for energy distribution and "generated power" (score 8) for monitoring and control have suitable scores, while the rest have low scores, below 5.

It is crucial to highlight that the external joint evaluation emphasized in the section 4.1 and the implementation of the technological functioning outlined in section 4.2 together form the entire framework for the industrial bioelectricity generation system implementation process. In this context, the process employed was based on the utilization of sugarcane, aiming to improve various aspects concerning lignin structure. These aspects include addressing fermentation inhibition, increasing the availability of fermentable sugars, minimizing the formation of undesirable by-products, and reducing pre-treatment costs. It is important to note that this approach can be further explored and adapted to suit other types of agricultural waste as well.

The main difficulties these companies face are related to technological characteristics for energy transmission, which can be explained by their small to medium size and limited implementation budget. They often require public or private investments to address these challenges effectively.

4. Implications

This section presents a broad discussion on the implications that this methodology may have, such as industrial, governmental, and sustainability implications.

4.1 Industrial Implications

In industry, energy management processes must be supported by a methodology, such as the one developed in this work, that meets the criteria of the energy generation index using biomass.

The processes and actions addressed (Tables 3-9) are based on operational adjustments, management, and cost systems, including improvements in the technological structure of the industries studied here. These companies will receive a diagnosis built by scenarios that may lead to the implementation of energy generated through biomass.

The model works as a guide for the decision maker in a company since an industry, mainly an SMC, does not have an internal structure capable of focusing on the consumption and improvement of renewable energy from bioenergy. Some barriers must be overcome so that companies can implement methodological measures for the use of bioenergy in a robust way, as the diagnosis shows. Similarly, the following authors add that barriers need to be overcome so that the use of bioenergy has a positive industrial implication: (Mayfield et al., 2007) shows that some difficulties in using this type of renewable energy, such as biomass in large quantities and a supply chain close to energy generation, are essential for an effective implementation of bioenergy. With this, it reduces the socio-environmental impact in the region to some extent (Kinab & Elkhoury, 2012) analyzed the cultural structure of the industrial sector in order not to harm energy generation. The repercussion of economic and environmental benefits are preponderant even as a specific brand of the company. (Wiredu et al., 2022) discussed the lack of specialized technical professionals to develop and carry out the construction and maintenance of bioenergy to facilitate industrial management. (How et al., 2019) reported that low quality machines operated by inexperienced consultants and technicians and low quality inputs negatively affect bioenergy production systems and have a negative implication.

The diagnostic model built through different scenarios in this study helps to overcome these barriers, as its availability is agile and easy to access, in this way, the company hopes to reduce the impacts that biomass may generate on the environment due to the lack of adequate treatment (as a result of environmental liabilities), at the same time using energy from other matrices, mainly fossil ones. As (Kinab & Elkhoury, 2012; Mayfield et al., 2007; Wiredu et al., 2022) demonstrated that the association of barriers within industries presents great difficulty in overcoming them, specifically the technological ones, as many companies have difficulty in developing a new technological framework that overcomes them.

4.2 Government Implications

Energy is an essential input for the development of a country. In Brazil, the national biofuel policy was defined in 2017 with the purpose of implementing sustainable development and reducing the emission of gases that worsen the greenhouse effect and reduce the socio-environmental impact. In general, the case studies discussed above show a need for help from government incentives. Policies demanding biofuels, which are linked to changing the national energy matrix, encourages public-private integration to achieve a general functionality of this guideline of the Brazilian government.

Considering the proposed structure shown in the case studies of companies A, B and C (Figures 7, 8 and 9), companies, even though they are from sectors that do not emit waste that can generate bioenergy, manage to develop a minimal structure so that they can achieve co-generation conversion and consequently reduce energy costs through government subsidies. Also, the region of Brazil they are in has a large amount of biomass residues used in small quantities in other structures that can be easily converted into bioenergy and reduce environmental liabilities. This stimulates companies to promote co-generation or even an external distribution co-generator to companies in the region and reduce impacts inherent to large amounts of lignocellulosic biomass.

In the architecture shown in Figure 2 and Table 1, the social aspect would stimulate the sociopolitical acceptability and creation of jobs. This would facilitate countries that have similar characteristics as Brazil (large territorial dimensions and economic possibilities) to have success in the improvement of governmental indicators. This governmental structure has already been portrayed by other authors using other methodologies, among them (Mousa et al., 2016), who verify that the implementation of biomass in India has a high potential for the implementation of bioenergy in steel mills. The companies studied here with this fuzzy model, however, require government subsidies, which are essential to encourage implementation. (Luthra et al., 2016) shows that, as the case study A, the high initial cost of technological adaptation is a limiting factor for the internal implementation of bioenergy generation. The authors report that the tendency to keep operating costs low makes the company's functionality viable. It is important to highlight that in Brazil, small and medium-sized companies have great difficulties in maintaining their operation and that around 60% go bankrupt in less than five years (Brazilian Institute of Geography and Statisticsa, 2023). (Vanegas Cantarero, 2020) show that these government policies stimulate the post-Covid-19 national and global energy transition process and that they stimulate a detachment from a national structure towards something more regionalized (such as the indicators shown in Table F), which could facilitate the implementation of easy and agile structures such as the bioenergy generation index of this work.

Similarly, (Yang et al., 2019) state that governments should subsidize the promotion of renewable energy for micro-, small and medium-sized companies as they are the ones most responsible for structural job creation. On the other hand, companies must improve their internal evaluations in relation to the consumption and cogeneration of this energy as the proposition of this method of industrial decision-making aims to avoid eventual economic losses of the company and of the investment itself.

4.3 Implications for Sustainability

Due to the environmental degradation level resulting from the rapid increase in energy demand due to productive and population growth, there is a global and a local effort to change the implementation of technologies that promote energy transition. The development of methodologies, such as the one in this article, promotes the implementation of renewable energy, such as bioenergy, in fighting climate change and alleviates various environmental concerns, such as the agreement signed at COP 27 by Brazil, which posits a reduction of GHG emissions to lower the Earth's temperature by around 1.5°C to pre-industrial levels.

The option of using bioenergy in the industrial sector also solves the energy loss during energy transmission by concessionaires and reducing impacts that affect sustainability through the decentralization of energy generation. The methodology proposed here helps to solve the problem of excessive energy consumption in the industrial sector, which consumes approximately 32.2% of the national energy matrix. The replacement of the current system for bioenergy generation should occur when there is adequate planning during the process of potential technological changes, as the case studies show, mainly the case A.

Location and land use already cause effects on integrated environmental and economic assessments, as (Bryan et al., 2014, 2016; Paterson & Bryan, 2012; Polglase et al., 2013) highlighted. This effect occurs when environmental, economic, and political conditions combine to make environment highly competitive and homogeneous for that purpose, such as the excess of biomass for energy generation in the place where the industries are located.

5. Limitations

As this is an initial work for the development of this proposal, some limitations are inherent to it. One of them is the greater scope of case studies to verify some characteristics that could tend to be homogeneous mainly in companies from different sectors and different sizes.

There is a need for a structure that encompasses different types of biomass bioenergy generators in order to verify the conversion potential and the demand of each sector. As it addresses a research topic that has a wide decision-making amplitude, different types of specialists are needed for the construction of the basic rules, in addition to the generation of weights to direct the best path, including the multiple visions of different types of impacts.

6. Conclusions and Future Work Perspectives

The fuzzy model proposed in this new scenario evaluation methodology aims to support decisions related to changing the type of industrial energy consumption to reduce socioenvironmental impacts. It addresses the commitment gap to the reduction of sustainability, governmental, and industrial issues in relation to generating energy using biomass. Therefore, the approach proposed here should also allow for new forms of planning and be a support tool for policy makers in understanding the structure of companies, providing valuable information for potential bioenergy programs.

The main contributions of this work are the development of a new methodology for diagnosing bioenergy in manufacturing companies using indicators that have uncertainties and inaccuracies. It contributes to decision-making by industrial managers through a structured method for bioenergy consumption.

Another central point is the analysis of the new methodology in micro-, small and medium-sized manufacturing companies in a developing country with a high demand for biomass for energy generation. The preliminary implementation in case studies reveals an energy generation potential of this type above the average. This important finding faces a great difficulty in formulating internal policies to reduce energy consumption due to the characteristics and losses of Brazil's energy matrix. The evaluation points out that, in the context studied, companies face a great challenge in improving technical, economic, and social aspects. The results suggest that additional efforts in adaptation and integration of constant technological maintenance may improve a system that facilitates the use of this type of energy.

The characteristics of the industrial EE model have the potential to adjust practices in the manufacturing industry, ensuring greater sustainability and allowing the possibility of crossing an energy transition barrier with industrial, solving an environmental liability and governmental implications.

For future work, other decision-making methods should be able to verify interrelationships between the various branches in the proposed model. A more in-depth study should also construct a decision-making structure for political managers who seek to implement this type of renewable energy in other sectors. In addition to developing relationships, studies should develop a specific structure for the industrial sector, studying the specificity of the potential of different types of biomass for energy generation, in addition to verifying the reduction of economic, social and environmental impacts with the implementation of bioenergy in companies in this region.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal and publisher adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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