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A biomass waste evaluation for power energy generation in Mexico based on a SWOT & Fuzzy-logic analysis

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ABSTRACT

Power energy generation in Mexico based on bioenergy is currently insignificant. However, the potential for taking advantage of biomass resources in the country is considerable. This article aims to evaluate the use of biomass waste for the Mexican energy transition in the near future. The methodology starts by identifying sites with biomass waste and establishing the conversion processes needed to produce electricity for each type of biomass. A SWOT analysis was implemented to define the criteria for evaluating all options on the same basis. The opinion of experts in energy systems was collected to assign priority to each criterion. A fuzzy-logic inference system was formulated to assess the options based on the quality of their attributes. The output obtained from the fuzzy analysis is a sustainability prioritisation of all options. We analysed a case study for the Baja California Sur (BCS) region, and the results show the prioritisation ranking of 24 alternatives regarding the sustainable use of bioenergy in the region and we made a proposal of an indicative plan to introduce bioenergy in the region from now until 2032. If the indicative plan were implemented, 61% of the power demand of BCS could be covered with bioenergy by 2032.

Keywords

Waste;
Bioenergy;
SWOT analysis;
Fuzzy logic;
Indicative planning;

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1. Introduction

Since the Paris Agreement in 2015, the global community has agreed that it is necessary to limit the global average temperature rise to well below 2°C and to make efforts to stay below 1.5°C [1]. The above requires greenhouse gas emissions to drop dramatically. However, the consumption of fossil fuels worldwide continues to increase. According to Our World in Data in 2019, around 64% of the global electricity came from fossil fuels [2].

Global efforts have been made to decarbonise the electricity sector using more renewable energies but with poor results over the mitigation goal. It is urgent that each country improves its power systems and incorporates strategies to carry out the transition. There are different studies mainly in the US, Canada and Switzerland that seek to decarbonise their electricity sectors, and show the possible solutions that can be carried out in those countries [3–5]. Similarly, other studies, such as Connolly & Mathiesen [6], carried out an analysis of having a 100% renewable power system in Ireland. Among the possible solutions, the authors conclude that it is necessary to use low-carbon sources and implement policies that promote the use of renewable energies.

Mexico is committed to reducing emissions in the medium and long term. The objectives are reflected in the Energy Transition Law, the General Law on Climate Change and the Nationally Determined Contributions (INDC) [7–9]. In power generation, a minimum share of 35% clean energy has been established for 2024 and 50% for 2050. However, fossil fuels dominate México's

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power generation system with a share of 72.15% (229.3 TWh) in 2020 [10]. In other words, wide efforts are still required to promote renewable and clean resources.

So, it is crucial to integrate all kinds of renewable energies into the system to accelerate the transition. Bioenergy is an option, which is obtained from the transformation of biomass waste and has been among the renewables the least used in Mexico for power generation. According to official information, bioenergy has participated every year less in the power energy mix with 5.2% (1.67 TWh/y) in 2018, 2.19% (0.71 TWh/y) in 2019 [11] and 0.2% (0.63 TWh/y) in 2020 [10]. Nevertheless, the country has a great diversity of biomass waste that can be transformed into biogas and later into electricity. Following Rios & Kaltschmitt [12] an average energy potential of 2,228 PJ/y can be obtained countrywide from biomass residues. The same authors [13] calculate a theoretical power generation of 167.9 TWh/y from organic waste. Flores et al. [14] indicate that the energy potential of woody forest residues is approximately 45.96 PJ/y. The Mexican National Atlas of Biomass of the National Inventory of Clean Energies (ANBIO) [15] shows the primary biomass generating sources that can be used for energy purposes, having an approximate amount of 278 million tons/y of waste throughout the country, with a potential of 2,980 PJ/y for energy purposes.

There is an extensive collection of studies on bioenergy and its energy applications both worldwide and in Mexico. To mention a few, Yaqoob et al. [16] survey the biogas generation potential for Pakistan and policies to support regulatory changes in the country. Lozano-García et al. [17] calculate the potential of some types of crops to generate electricity in Mexico. Torre-Tojal et al. [18] have made biomass estimates using LiDAR data. Mukherjee et al. [19] designed biodigesters to process livestock. Mohaghegh et al. [20] studied the latest advances in integrating hybrid system plants with solar PV for electricity generation. At the same time, Thain & DiPippo [21] apply hybrid systems with geothermal. On the other hand, Mallaki & Fatehi [22] propose a design for biomass plants that process palm for electricity generation and obtain some economic and environmental parameters from their creation. Lybaek & Kjaer [23] offer a strategic plan with improvements for the use of biogas in Denmark. Kurbatova [24] discusses the economic benefits of producing biogas with cattle manure in Ukraine. Martínez-Guido et al. [25], carried out a strategic plan based on energy optimisation for Mexico, promoting biomass pellet plants and thus generating electricity.

It should be noted that none of the previously reported studies has considered all the evaluation multi-criteria together for the actual implementation of electricity production projects. The authors only focus their studies on analysing a single type of waste. As far as we are concerned, we evaluated the performance of four types of bioenergy wastes (bovine manure, pig manure, urban solid waste and wastewater treatment) considering the properties of each waste, the required processing technology for each waste type, the needed waste transportation distance, the avoided emissions amount that can be obtained, the policy incentives can be applied, the interconnection distance to the grid, the annual availability of waste, job creation, costs and as the main result we calculate the amount of power generation that bioenergy can provide to the system by using each alternative (characterised by the site, biomass type and process technology). Therefore, applying a multicriteria decision-making methodology to carry out the integral evaluation of bioenergy in the power sector context is recommended. As we will show forward in this paper, 24 alternatives must be evaluated under the same basis assessment.

First, a SWOT analysis was applied to select a set of criteria in terms of strengths, weaknesses, opportunities, and threats that each bioenergy alternative can provide to the power sector. Second, a Fuzzy logic analysis was used to aggregate all the individual criteria in only one qualification for each alternative. Then we combined both approaches into a SWOT & Fuzzy logic analysis. This research aims to evaluate sites with biomass waste potential for power generation, by identifying the main criteria that would support the decision-makers to define the future investments. The goal is to obtain a prioritisation of sites based on various criteria of sustainability, and based on these results, to recommend a long-term indicative plan to introduce bioenergy in the electricity sector of Mexico. For the development and testing of the methodology, this paper shows a case study for the Baja California Sur (BCS) Peninsula in Mexico. Today, this is a region without electrical interconnection with other regions of the country [26], without natural gas transportation duct infrastructure and with inferior management of its biomass waste [27]. Applying a methodology that makes it possible to identify where the most significant cost benefit could be achieved becomes a valuable tool for decision-makers, which is the main contribution of this work.

The research work has been divided as follows: Section 2 includes a literature review. Section 3 describes the SWOT Fuzzy-logic methodology. Section 4 presents its implementation with a case study. In section 5, the results are discussed, and at the end the conclusions of the work.

2. Literature Review

According to the Global Bioenergy Statistics 2020 [28], 637 TWh/y of electricity were generated in the world in 2018, where Asia was the largest producer with 38% of the total (243 TWh/y), followed by Europe with 35% (225 TWh/y) while the entire American continent produces 25% (163 TWh/y) of the total. According to the International Energy Agency (IEA) [29], in the year 2020, there was a power energy increase of 12% compared with the year 2018 of generation with bioenergy to reach 718 TWh/y, and in a scenario (Net Zero) IEA predicts that by 2030 1,407 TWh/y of electricity could be generated with bioenergy.

Policies supporting the development of biomass energy have been improving throughout the world, and these policies have been implemented differently in each country. According to Sam Cross et al. [30], countries such as Finland, Sweden, Denmark, and the UK have solid regulatory policies to accomplish decarbonisation targets that have had a significant impact on the levels of bioenergy generated. These countries' main support mechanisms to promote bioenergy are government support, regulated tariffs, and infrastructure and facilities planning. However, they conclude that policy is important in promoting bioenergy, but it is not a unique correlation. Specifically, bioenergy is driven by multiple other factors, and these vary according to each country and the conditions there exist.

For countries with no solid public policies, Abdallah et al. [31] propose that it is imperative to have energy reforms with a sustainable development approach. These reforms could help to promote electrification and analyse how viable it is to follow already established policy models from other countries or how to adjust these policies according to the behaviour of each country. The previous is important since renewable energies such as bioenergy can be promoted according to the needs and trends in the world.

Bioenergy in Mexico has not been used as expected by the ecologists. However, today there are regulations in the country that promote bioenergy. According to the Law for the Promotion and Development of Bioenergy published by the Chamber of Deputies of the H. Congress of the Mexican Union [32], describes bioenergy waste is obtained from organic matter from agricultural, livestock, forestry activities, fishing waste, domestic, commercial, industrial, etc. Likewise, it is mentioned that its processing must comply with the official Mexican standards to ensure safety and environmental aspects for the sustainable production of inputs. This law leaves the different applications that can be carried out once bioenergy is produced, such as the production of electricity. Still, it endorses promoting production and scientific and technological research to favour the country's sustainable development.

Based on the Special Program for the Use of Renewable Energies, biomass power generation in the country has been decreasing over the years. In 2020 bioenergy produced only 0.63 TWh/y [11], approximately 90% came from the direct combustion of sugarcane bagasse and the rest from the production of biogas from different types of waste. Regardless of having low bioenergy participation, the document Update of the Transition Strategy to Promote the Use of Cleaner Technologies and Fuels [33] stated that biomass has a significant potential to increase the energy supply in the country. And that it can be used directly for heating and power generation or can also become substitutes for oil and gas.

Despite having documents that promote the use of bioenergy for electricity generation, the existing policies in Mexico are minimal compared to other countries, so it is necessary to carry out plans or strategies that promote energy production from biomass residues.

3. Methodology

This section explains the importance of using a multicriteria decision-making methodology to evaluate biomass residues for electricity generation. In this study, we considered pig and bovine manure, livestock and urban solid wastes. Information was sought on the biomass resources available in different sites of the study region; this includes the location of the site, the type of biomass that exists in the place and the potential annual production of biomass available in tons reported in the ANBIO. Processing technologies were identified to condition it from its original state to suitable conditions for its use as fuel in the power plant which will be connected to the electrical grid. This is the kind of problem where there are multi alternatives and multicriteria that influence sustainable decisions. Each existing alternative has its attribute in each criterion, and there is not an alternative having the best score in all the criteria or having all the worst. Besides, decision-makers want to rank the existing alternatives from the best to the worst considering their global performance.

There are various methodologies for decision-making analysis applied to energy, highlighting life cycle assessment (LCA), cost-benefit analysis (CBA), and multicriteria decision aid (MCDA). The latter combines techniques based on the assignment of weights [34], [35]. E.g., Kaya & Kahraman [36] collectively evaluate various types of energy using a fuzzy TOPSIS analysis, obtaining which kind of energy gets the best marks with some evaluated criteria. Ervural et al. [37] combine SWOT, AHP and TOPSIS processes to evaluate strategic plans in Turkey to define which should be followed. Ribeiro et al. [38] use MCDA methods to evaluate expansion plan scenarios. All these previous studies have in common that they assess expansion plans of the power energy system or evaluate scenarios by identifying criteria.

Compared to other multicriteria decision-making methods, combining SWOT and Fuzzy Logic in our study is done with the idea of being able to identify, through SWOT, the strengths, weaknesses, opportunities and threats that are detected in Mexico regarding the use of bioenergy and its possible incursion in the power system. On the other hand, fuzzy logic was used to build an aggregated fuzzy function considering all the parameters from the SWOT analysis to be able to qualify the sites where a bioenergy power plant could be installed with the main purpose of developing a subsequent strategic plan for future investments in bioenergy, the sites were ranked according to their global sustainability.

3.1. SWOT & Fuzzy-logic methodology application.

The proposed methodology comprises four phases, as shown in Figure 1. Phase 1 identifies each of all the alternatives: sites, kinds of waste in them, and type of processing technologies to condition the waste into fuel for the power plant. Phase 2 consists of applying SWOT analysis to select the evaluation criteria and the assignment of their importance through the collection of opinions and judgments from experts in energy sustainability. In Phase 3, the Fuzzy-Logic method is applied to qualify the alternatives in terms of their attributes in each criterion. In Phase 4, the final ranking of the alternatives is obtained and then it is used to generate an indicative plan for future generation capacity penetration with bioenergy in the analysed region of BCS.

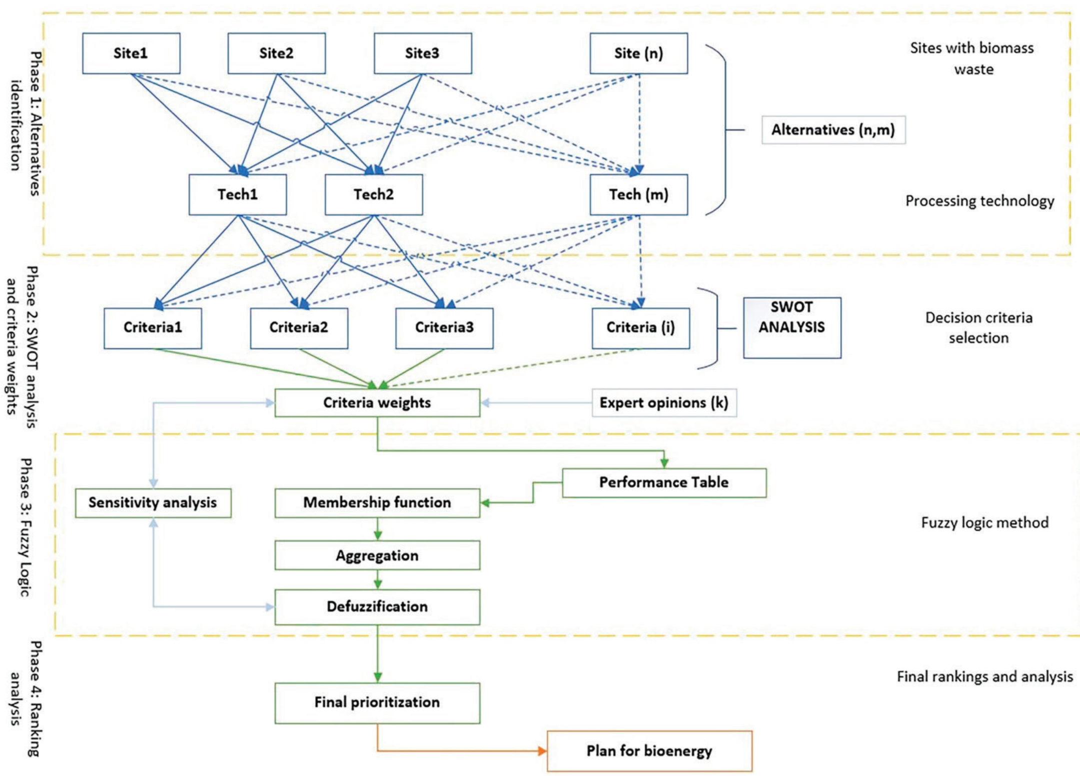

Figure 1: Schematic diagram of the proposed methodology.

3.2. Phase 1: Alternatives identification

For this phase, the alternatives to be evaluated are identified, compared and finally ordered according to their sustainability qualities. The following steps were followed:

a) The biomass at each site was related to the possible applicable processing technologies. The combination represents the alternatives (site & technology). If we have *n* sites and *m* possible technologies to process the waste from each site, the number of the alternatives to be evaluated will be $n \times m$.

b) Data was prepared for each identified alternative, including energy frameworks, environmental parameters and costs.

3.3. Phase 2- SWOT analysis and criteria weights

A SWOT analysis, Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) has been used as a strategic planning tool, an effective technique for analysing complex problems in different areas, reducing failures and taking advantage of projects or government plans. Taking into account this, in this work, we decided to apply a SWOT analysis to select the criteria that serve as a basis for evaluating the current situation of bioenergy for power energy generation in Mexico. Based on some SWOT analyses found in the literature for the evaluation of bioenergy projects [39–42], ten criteria were defined and divided into internal factors "S" and "W" and external factors "O" and "T". A group of experts in energy sustainability who participated in this phase, proposed the criteria and their importance by assigning weights. Figure 2 highlights the different components of the SWOT analysis that was performed.

The evaluation criteria that qualify the different alternatives based on the internal and external factors proposed by the experts are described below.

3.3.1. Selection of evaluation criteria for strengths

- S1: Daily organic waste collection

Daily organic waste collection refers to tons of organic matter waste collected on-site to be processed in the biogas plant. The greater the quantity, the greater the use of biomass, and its unit of measurement is tons per day (t/d).

- S2: Generation of new jobs

Jobs generation will be considered to collect the residue, the installation and the operation until the end of the plant's life. It is measured in the number of jobs per

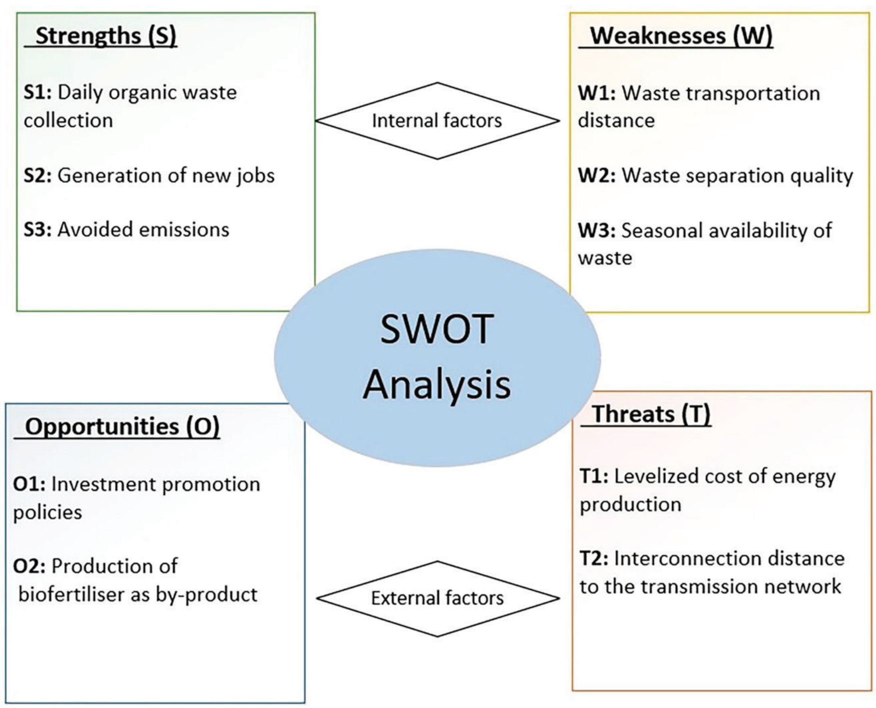

Figure 2: SWOT Analysis of the bioenergy use for electricity generation.

installed capacity. It is a fundamental criterion for evaluating social benefits since a project that generates jobs ensures better economic and social development for the region and it is assumed that the more jobs it generates, the higher its productivity.

- S3: Avoided emissions

The avoided emissions refer to greenhouse gas emissions that, being a bioenergy project, are not emitted, leading to a negative carbon footprint. Therefore, it is necessary to consider the number of total emissions that can be avoided with bioenergy. Mitigation due to waste disposal, fossil fuel replacement mitigation, and clean energy mitigation are identified. These avoided emissions are measured in tons of carbon dioxide equivalent per year (tCO2e/y).

3.3.2. Selection of evaluation criteria for weaknesses

- W1: Waste transportation distance

It is the distance in kilometres (km) between the waste collection location and the location of the waste processing plant.

Ideally, the processing plant should be installed at the site where the waste is produced to avoid additional transportation costs. However, this is not always possible because the generating plant must be connected to the transmission line and, likewise, the biogas production plant near the power plant.

- W2: Waste separation quality

The criterion refers to the quality of separation of organic and non-organic waste. It was defined to consider the type of waste that requires recycling since it arrived mixed with other waste that cannot necessarily be used in the bio-digestion process. Currently, waste management in Mexico has not been adequately promoted; classification and separation by type of waste at home, shops, or others, is not enforced.

Therefore, it is understood that it is a process that, at least in Mexico, must be carried out gradually until integral waste management is achieved. This is an important criterion but difficult to quantify. The best way is to consider it a factor between 0 and 1, where 0 indicates that the waste is mixed and must be separated to be processed, and a value of 1 when correctly separated.

- W3: Seasonal availability of waste

The seasonal availability of waste refers to the behaviour that residue production will have during the different seasons of the year. Some residues, mainly forestry, cannot be available during all months of the year. For this reason, it is essential to consider this behaviour as a weakness since it is necessary to analyse how much it would affect not having the plant continuously operating at its maximum power. This is represented by an availability factor which considers the ratio between the number of hours in which the resources will be available to operate the plant and the number of hours in the year.

3.3.3. Selection of evaluation criteria for opportunities

- O1: Investment promotion policies

Government incentives are mechanisms that support the implementation of energy projects in the country. It is necessary to identify whether there are subsidies to support the emergence of bioenergy for power generation. A review was conducted to identify any support or other funds that the government has earmarked for bioenergy projects in the past. We found that Mexico's Ministry of Agriculture and Rural Development (SAGARPA) supported projects where biomass waste is animal manure. On the other hand, there are some supports applied to renewable energies such as the Clean Energy Certificate and supports to favour the reduction of tons of garbage that would have to be sent to final disposal in sanitary landfills when the processing is not done. In addition, a percentage is left for "other supports" in case any other option is identified that is not contemplated at the moment.

We consider four options with the same score:

1. SAGARPA support 0.25
2. Clean energy certificate 0.25
3. Reduce garbage support 0.25
4. Other supports 0.25

A site with the four supports gets a score of 1.

- O2: Production of biofertiliser as a by-product

The criterion represents the number of tons of biofertiliser per year (t/y) produced by the conversion process. This is seen as an opportunity to acquire a non-energy profit. From biodigestion, in addition to the amount of biogas that it can produce, fertiliser can be obtained, which has a value associated with other markets. The decision-maker will be able to decide what use to give it.

3.3.4. Selection of evaluation criteria for threats

- T1: Levelized cost of energy production

This criterion represents the cost of generating electricity from the bioenergy plant. It includes the costs of the

Table 1: Components of the SWOT analysis.

SWOT Components	Criteria (*i*)	Unit	Category
Strengths (S)	Daily organic waste collection (S1)	t/d	B
	Generation of new jobs(S2)	Number of jobs/y	B
	Avoided emissions (S3)	tCO_2e/y	B
Weaknesses (W)	Waste transportation distance (W1)	km	C
	Waste separation quality (W2)	Factor	C
	Seasonal availability of waste (W3)	Factor	C
Opportunities (O)	Investment promotion policies (O1)	Factor	B
	Production of biofertiliser as a by-product (O2)	t/y	B
Threats (T)	Levelized cost of energy production (T1)	USDc/kWh	C
	Interconnection distance to the transmission network (T2)	km	C

B: Benefits (the more, the better) C: Costs (the less, the better)

Remark: S2, S3 and T1 depend on the site and the processing technology type, while the rest of the criteria depend only on the site.

biogas plant to process the biomass waste at the installation site and the costs of the equipment that will convert the biogas into electricity. It is measured in US dollar cents per KWh (USDc/kWh). In México, the LCOE is still high, mainly for the biogas process plant; for that reason, the criteria T1 considers in this study as a threat. When the costs decrease, this criterion can belong to another category.

- T2: Interconnection distance to the transmission network

This criterion refers to the distance in kilometres from the generating plant to the closest interconnection node in the transmission network. The decision-maker must consider the costs of electricity transmission from the power plant to the charging area. These costs are proportional to the distance between the power plant and the closest interconnection node to the transmission line.

3.3.5. Summary of components of the SWOT analysis

Table 1 shows the components of the SWOT analysis that were used to evaluate the alternatives for electricity production from biomass. Strengths and opportunities were considered in the Benefits category, and weaknesses and threats in the Costs category. What is sought is to qualify the alternatives based on the lowest cost/benefit ratio.

3.3.6. Assignment of the weight for the criteria.

For decision making, it is necessary to assign a value relative to the importance of each criterion.

The calculation of the weights is obtained from the opinion of the group of experts k (E_1, E_2, E_k ..., E_K), who evaluate each criterion i (C_1, C_2, C_i..., C_I), chosen from the SWOT analysis. The experts assigned to each criterion a numerical term y in a range of preferences from 1 to 5 according to their experience in the subject. Where 1 is the lowest value, and 5 is the highest, forming a matrix ($I \times K$) to obtain a vector corresponding to the weight w_i that brings together the experts' opinions. According to the importance given by the experts, the weight calculation will change by type of criterion and is represented in equation 1.

$$w_i = \frac{\sum_{k=1}^{K} y_{ik}}{\sum_{k=1}^{K} \sum_{i=1}^{I} y_{ik}} \qquad \forall i \in I \tag{1}$$

These weights are helpful to favour the quality of decision-making and are applied in the fuzzy methodology which is explained in the next section.

3.4. Phase 3: Fuzzy logic analysis

The implementation of a fuzzy inference system (FIS) to evaluate the criteria that come from the SWOT analysis was carried out to evaluate the use of biomass waste for power generation with two objectives:

1. Identify and rank the best sites where biomass waste processing is applied and have the best chance of success when carrying out the project.
2. Compare the processing technologies and select the one that uses better the biomass resources fed.

The fuzzy logic methodology proposed by Zadeh was chosen [43] since it is flexible and an evaluation as specific as necessary can be carried out. Fuzzy logic deals with reality, handless the concept of truth value that ranges between completely true and completely false (0-1). For energy systems fuzzy, is one of the most used methodologies because of its capacity to represent uncertainty.

The fuzzy logic system works from the construction of a FIS. By defining the input and output variables and their membership functions [44]. By defuzzification, the results are transformed into a numerical value for interpretation [45].

For the fuzzy logic methodology, the following steps are followed:

Step 1: Information about the alternatives and creation of a performance evaluation matrix

The information of criteria for all the alternatives $n \times m$, which correspond to the n sites and the m technology processes must be put in the performance evaluation matrix.

Step 2: Description of fuzzy sets and membership characteristics (Diffusion).

The input variables that describe the system's behaviour are described in fuzzy values. To achieve the transformation, the ranges of variation of the input variables (criteria *i*) and the fuzzy sets associated with their respective membership functions that vary between 0 and 1 must be defined.

In Figure 3, two formats of membership functions are presented, the left side for strengths, and the right side for threats. Different linguistic values are assigned to qualify each criterion, and each value represents a fuzzy set, forming triangular functions (TFNs). For each linguistic value, the labels "Good (G)", "Fair (F)", and "Bad (B)" are used.

Step 3: Fuzzy Rules (Rule Evaluation)

Fuzzy rules are used to infer an output based on the input variable. Fuzzy logic is based on heuristic rules of the form If <condition> then <consequence>. These rules connect the membership variables using logical operators. They are built from the TFNs and the operators, following a logic of what the result would be expected to be.

The FIS tool created 30 fuzzy inference rules using the operator "AND" with the scalar product's implication to construct the output variable's membership function, considering the linguistic variables G, F, B. An example of fuzzy rules can be the following:

- If S1 is Good & regardless of other parameters THEN, the use of that alternative is Good;
- If S1 is Fair & regardless of other parameters THEN, the use of that alternative is Fair;
- If S1 is Bad & regardless of other parameters THEN, the use of that alternatives is Bad;

In Table 2, the fuzzy rules are summarised; the AND operator is represented by the symbol &, G means Good, F means Fair, and B means Bad.

Step 4: Other fuzzy parameters

- For the fuzzy inference system, we selected a Mamdani type approach.
- The aggregation method used in the FIS tool is the sum of the membership functions

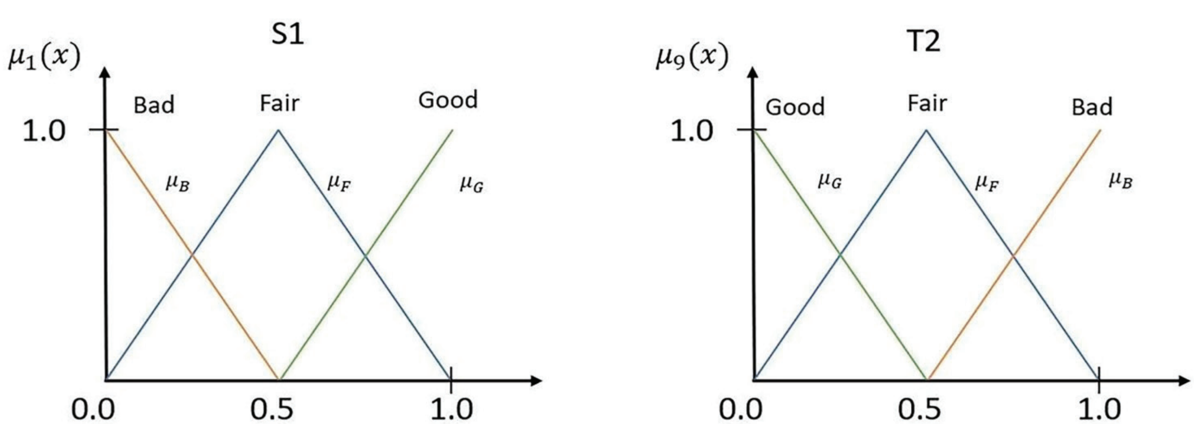

Figure 3: Example of definition of membership variable.

Table 2: Heuristic fuzzy logic rules.

Rule	IF S1 &	S2 &	W1 &	W2 &	W3 &	O1 &	O2 &	O3&	T1 &	T2 &	THEN
1	G	-	-	-	-	-	-	-	-	-	G
2	F	-	-	-	-	-	-	-	-	-	F
3	B	-	-	-	-	-	-	-	-	-	B
4	-	G	-	-	-	-	-	-	-	-	G
5	-	F	-	-	-	-	-	-	-	-	F
6	-	B	-	-	-	-	-	-	-	-	B
…	…	…	…	…	…	…	…	…	…	…	…
28	-	-	-	-	-	-	-	-	-	G	G
29	-	-	-	-	-	-	-	-	-	F	F
30	-	-	-	-	-	-	-	-	-	B	B

Step 5: Diffuse outputs and defuzzification

In this step, all the fuzzy outputs formed in the inference stage are combined to create a single output with a single value that will be the output value of the function. The centroid function method was used to find the average weight of the membership function of the fuzzy output.

In this work, the Fuzzy Logic Toolbox of MATLAB was used to elaborate the FIS [46]. The tool normalises the data of the evaluation matrix. The results are shown in a range [0 1]. The closer to 1, the better result. However, it is recommended to perform a sensitivity analysis to know the behaviour of the study variables.

3.5. Phase 4: Final evaluation

With all the above information, the fuzzy inference system is formulated to evaluate biomass waste for electricity generation, and the final prioritisation is obtained. With this information, the decision-maker will be able to generate strategies for implementing policies to promote bioenergy use in the power sector. In this paper, we propose an indicative plan for bioenergy capacity installation deployment.

4. Case study research

To examine the applicability of the proposed methodology, the Baja California Sur (BCS) region was studied. This is a region located in the northwest of the country, which is an isolated electrical system that is not linked to the Interconnected National Electric System. The BCS region also has big problems supplying fossil fuels to generate electricity and requires a large amount of diesel and oil to operate the thermal power plants. The current generating capacity in BCS is 1,048 MW, where 93.7% is from fossil fuel. Consequently, all clean energy alternatives should be considered in the near term. Hence, there is an opportunity to look at biomass waste as part of the solution in that region.

For this study, information from ANBIO was collected, identifying twelve sites with different biomass waste to be analysed in the BCS region (N=12). Figure 4 shows the selected sites, detailing the location and type of biomass residue at each site.

Table 3 shows the location, the waste type and a short name to identify the site quickly. According to the type of biomass available in the BCS region, two types of biodigesters could be chosen to produce biogas: anaerobic lagoon biodigestion ALD, and continuous stirred tank reactor CSTRD. Therefore, there are 24 alternatives to evaluate.

4.1. Criteria evaluation

The methodology was applied to the case study. A group of experts in energy systems and the bioenergy area in Mexico was called upon; all of them have a PhD and have worked in the energy area in Mexico. Six experts were interviewed (E_1, E_2, E_3, E_4, E_5, E_6). Table 4 shows the weights based on the expert opinion for each criterion, and the final weight that each criterion would have after applying the methodology described in section 2 by using equation 1. Information about the expert group is shown in Appendix 1.

4.2. Obtaining information about the alternatives

Based on the methodology described in section 2, it is necessary to quantify each criterion selected for each alternative. The potential of the waste is the daily

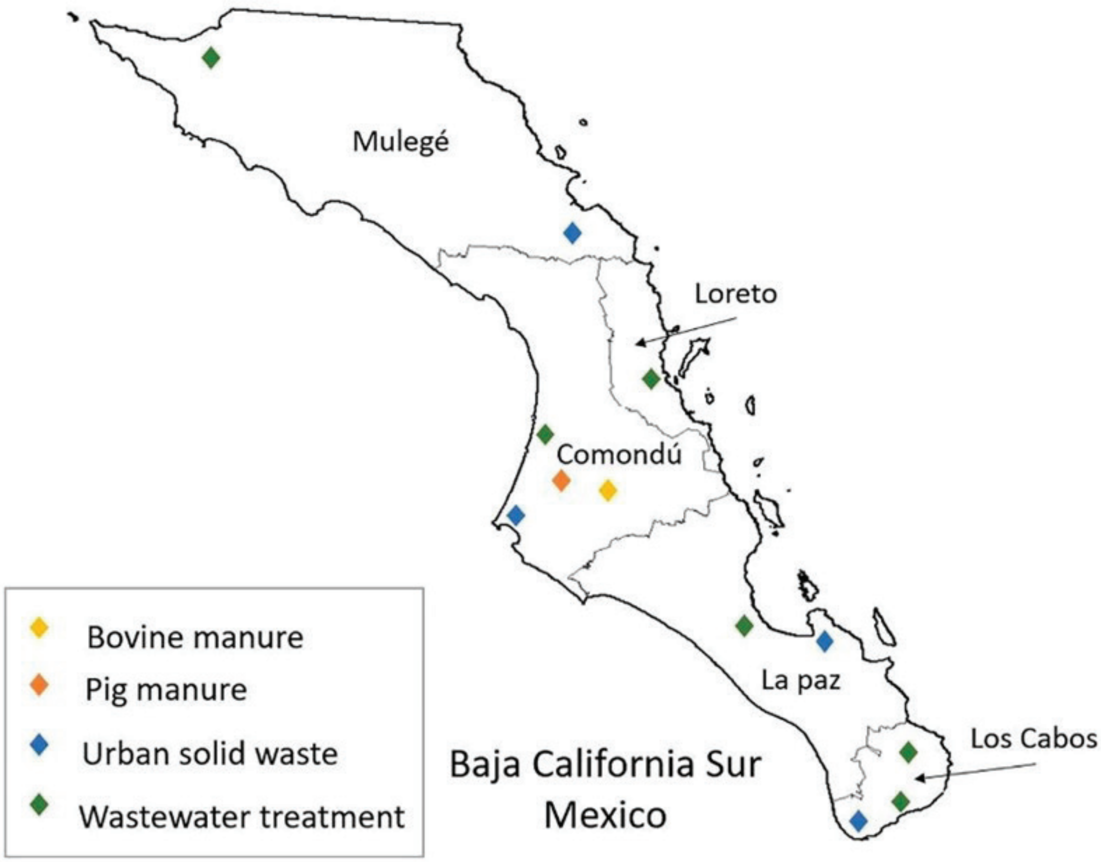

Figure 4: Identification of sites with biomass waste in the BCS region.

Table 3: Description of sites with biomass waste in the BCS region.

Site	Municipality	Waste type	Site-waste type (Short name)
Site 1	Comondú	Bovine manure	s1 BM
Site 2	Comondú	Pig manure	s2 BM
Site 3	Los Cabos	Urban solid waste	s3 USW
Site 4	La Paz	Urban solid waste	s4 USW
Site 5	Comondú	Urban solid waste	s5 USW
Site 6	Mulegé	Urban solid waste	s6 USW
Site 7	Mulegé	Wastewater treatment	s7 WWT
Site 8	Loreto	Wastewater treatment	s8 WWT
Site 9	Comondú	Wastewater treatment	s9 WWT
Site 10	La Paz	Wastewater treatment	s10 WWT
Site 11	Los Cabos	Wastewater treatment	s11 WWT
Site 12	Los Cabos	Wastewater treatment	s12 WWT

Table 4: Expert-weighted evaluation

High-level objective	Criteria abbr.	E1	E2	E3	E4	E5	E6	Final weights
Strengths	S1	5	5	5	5	4	4	0.131
	S2	5	5	3	4	5	5	0.126
	S3	5	4	4	5	5	5	0.131
Weaknesses	W1	3	4	2	3	2	5	0.089
	W2	3	2	3	1	4	3	0.075
	W3	3	2	4	1	3	1	0.065
Opportunities	O1	2	3	1	3	4	4	0.079
	O2	3	2	3	3	2	3	0.075
Threats	T1	4	5	5	3	5	4	0.121
	T2	4	3	3	4	4	5	0.107

organic waste collection (S1) was calculated with information from ANBIO. The data for the generation of new jobs for the S2 criterion is calculated depending on the size of the plant. According to the research of Thornley et al. [47] an average of 10 jobs-year can be generated for each MW of electrical power plant. Therefore, for the twelve analysed sites, a particular bioenergy plant design was defined where ALD and CSTRD biodigestion technologies were considered as possible options for processing (M=2).

Criterion W1 recommends that for USW waste, the waste processing plant is located no more than 1.5 km from where the sanitary landfill is located to separate the waste that is useful for obtaining energy. Criteria W2, W3 and O1 are calculated using the information described for each criterion in section 3.3.

The specific data from the operation of the plant, emissions avoided (S3), fertiliser as a by-product (O2) and technological costs (T1) were obtained from the Biogas Tool explicitly developed for Mexico created by the Danish Energy Agency, IBtech & Energy Analysis [48]. This tool is developed to design biogas production plants and power generation from different waste. As input, the tool has the necessary information about the waste at each site. As an output, it generates a specific theoretical design of a biogas plant that produces electricity (it includes all the necessary equipment for the pre-treatment and energy conversion).

To obtain the interconnection distance to the transmission network (T2), the one-line electrical diagrams of the National Electric System [49] prepared by t Mexico's National Centre for Energy Control (CENACE) were reviewed to identify the proximity of the interconnection node with the biomass site. The distance between the site and the closest transmission node is estimated through the Google Maps application. All the data are combined, and the performance evaluation is presented in Table 5.

The FIS evaluates the matrix, prioritising the 24 alternatives to evaluate for this study region.

5. Results and discussion

This section is divided into three main parts. The first corresponds to the final results for the SWOT & Fuzzy-logic methodology, the second shows a sensitivity analysis to prove the correct functioning of the FIS, and the third contains a bioenergy plan in the BCS region.

5.1. Final analysis results

The evaluation of the use of biomass waste following the SWOT & fuzzy-logic methodology is aimed at investors and decision-makers of local government entities who wish to invest in plants for power generation with bioenergy. The goal is to obtain the highest performance. When conducting the FIS evaluation, the final grades of the 24 alternatives of the BCS case study are extracted (see Figure 5).

Using the FIS evaluation made it possible to rank the alternatives in terms of sustainability. We must select the best option for each site. Excluding sites 1, 2,7,9 and 11, in all the sites the CSTRD technology got a better score than ALD.

5.2. Sensitivity analysis

We are interested in examining how the change in some criteria or the assigned weights affects the evaluation. This is very useful since it allows us to

Table 5: Performance evaluation table

Alternatives	Attributes of criteria*									
	S1	S2	S3	W1	W2	W3	O1	O2	T1	T2
A1: s1 BM_ALD	28	11.00	1,387	0.00	1.00	0.65	0.25	276.87	43.5	9.96
A2: s1 BM_CSTRD	28	13.00	1,696	0.00	1.00	0.65	0.25	276.87	66	9.96
A3: s2 PM_ALD	12.6	2.00	287	0.00	1.00	0.65	0.25	500.25	103.3	15.42
A4: s2 PM_CSTRD	12.6	3.00	351	0.00	1.00	0.65	0.25	500.25	136.6	15.42
A5: s3 USW_ALD	117.7	36.00	4,808	1.50	0.00	0.78	0.50	2,032.37	17.6	6.56
A6: s3 USW_CSTRD	117.7	44.00	5,877	1.50	0.00	0.78	0.50	2,032.37	26.2	6.56
A7: s4 USW_ALD	124.3	38.00	5,078	1.50	0.00	0.78	0.50	2,146.43	17.4	1.07
A8: s4 USW_CSTRD	124.3	47.00	6,206	1.50	0.00	0.78	0.50	2,146.43	26	1.07
A9: s5 USW_ALD	35	11.00	1,428	1.50	0.00	0.78	0.25	603.49	24.8	34.07
A10: s5 USW_CSTRD	35	13.00	1,745	1.50	0.00	0.78	0.25	603.49	35.1	34.07
A11: s6 USW_ALD	58.3	9.00	1,192	1.50	0.00	0.78	0.25	503.77	26.9	127.00
A12: s6 USW_CSTRD	58.3	11.00	1,457	1.50	0.00	0.78	0.25	503.77	37.6	127.00
A13: s7 WWT_ALD	101	8.00	1,026	0.00	1.00	0.75	0.00	250.23	34.1	111.12
A14: s7 WWT_CSTRD	101	10.00	1,254	0.00	1.00	0.75	0.00	250.23	50.3	111.12
A15: s8 WWT_ALD	60	4.00	438	0.00	1.00	0.75	0.00	149.37	63.9	6.17
A16: s8 WWT_CSTRD	60	5.00	749	0.00	1.00	0.75	0.00	149.37	61.8	6.17
A17: s9 WWT_ALD	120	9.00	1,225	0.00	1.00	0.75	0.00	298.75	31.7	22.00
A18: s9 WWT_CSTRD	120	11.00	1,497	0.00	1.00	0.75	0.00	298.75	47.3	22.00
A19: s10 WWT_ALD	644.7	50.00	6,579	0.00	1.00	0.75	0.25	1,604.42	24.2	1.03
A20: s10 WWT_CSTRD	644.7	61.00	8,041	0.00	1.00	0.75	0.25	1,604.42	31.7	1.03
A21: s11 WWT_ALD	301.4	12.00	1,582	0.00	1.00	0.75	0.00	4.29	43.3	1.63
A22: s11 WWT_CSTRD	301.4	13.00	1,758	0.00	1.00	0.75	0.00	4.29	67.7	1.63
A23: s12 WWT_ALD	119	9.00	1,223	0.00	1.00	0.75	0.00	298.20	38.1	1.11
A24: s12 WWT_CSTRD	18.91	11.00	1,495	0.00	1.00	0.75	0.00	298.20	59.7	1.11

* The units of measure for each attribute are shown in Table 1.

identify the behaviour of the results under different assumptions. Two different analyses are carried out, which are shown below:

5.2.1. Value function sensitivity

A sensitivity analysis of the value function is performed to verify that the FIS works congruently. Alternative A24 was chosen to perform the relevant sensitivity tests. For this analysis, tests were carried out using the same weights given by the experts, modifying the attributes that qualify the criteria.

a) Test 1: a criterion with Costs category T1 is chosen; the criterion is increased and reduced by 30%. Creating the High T1 and Low T1 results.
b) Test 2: a criterion with Benefits category S3 is chosen, the value of the criterion is increased and reduced by 30%. Creating the High S3 and Low S3 results.

Figure 6 shows that the tests detect the effect of the expected behaviour for the two types of criteria, Costs and Benefits. In Test 1 with the assumption of High T1, the score of the alternative is decreased when the cost criterion increases. The site's overall rating decreases; inversely, with the Low T1 assumption, the rating increases. For Test 2 with the assumption of High S3 the benefit, criterion increases the site's overall rating, and Low S3 decreases its rating.

5.2.2. Weights sensibility

A sensitivity test was performed under the assumption of maintaining the weight of the 10 criteria with the same importance $w_i = 0.1$; creating the Equal Weighted result.

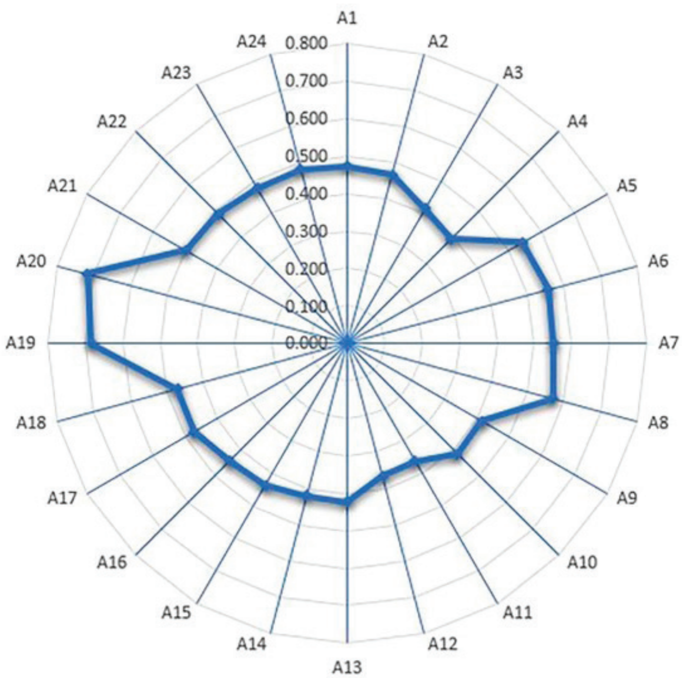

Figure 5: Expert weighted score, FIS results.

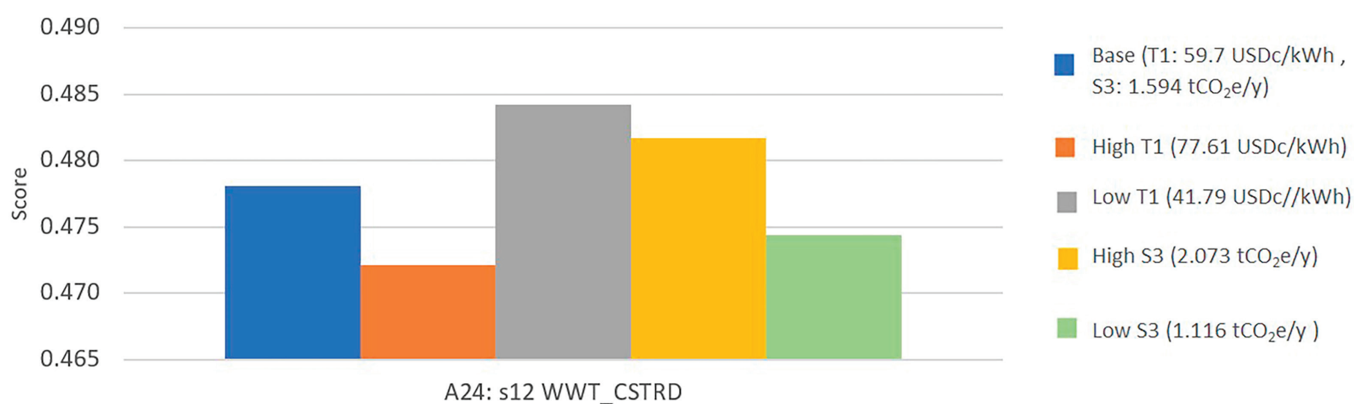

Figure 6: Value function sensitivity

Figure 7 compares the Expert-weighted evaluation with the Equal Weighted evaluation. It can be observed that the change of weights does not significantly alter the order of priority of the highest scores, which gives reliability to the methodology since the allocation of weights does not change the results. Moreover, it is observed that sites are competing for the same place, which indicates that the opinion of the experts is valuable since it helps define the final decision of the study.

Twelve sites with two technology options were evaluated. Figure 8 shows the best alternative for each site ranked from best to worst in terms of performance.

Two types of biodigesters were compared. The CSTRD biodigester obtained better marks for most sites, except for s2 and s12 sites. So, it would be the technology to be installed in each site to obtain higher waste yields. However, the methodology is flexible to evaluate when there is information on more than one technological option for waste processing.

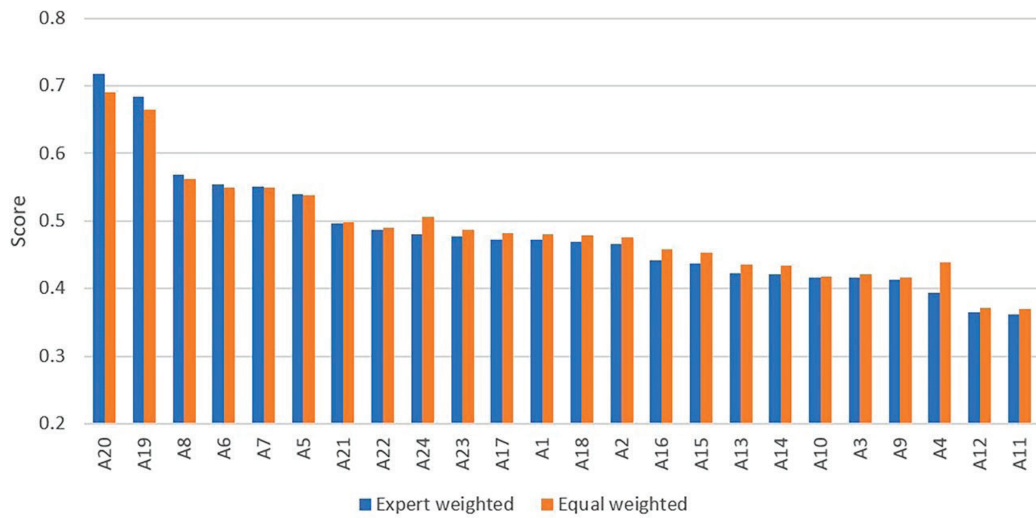

Figure 7: Weight's sensitivity analysis comparison.

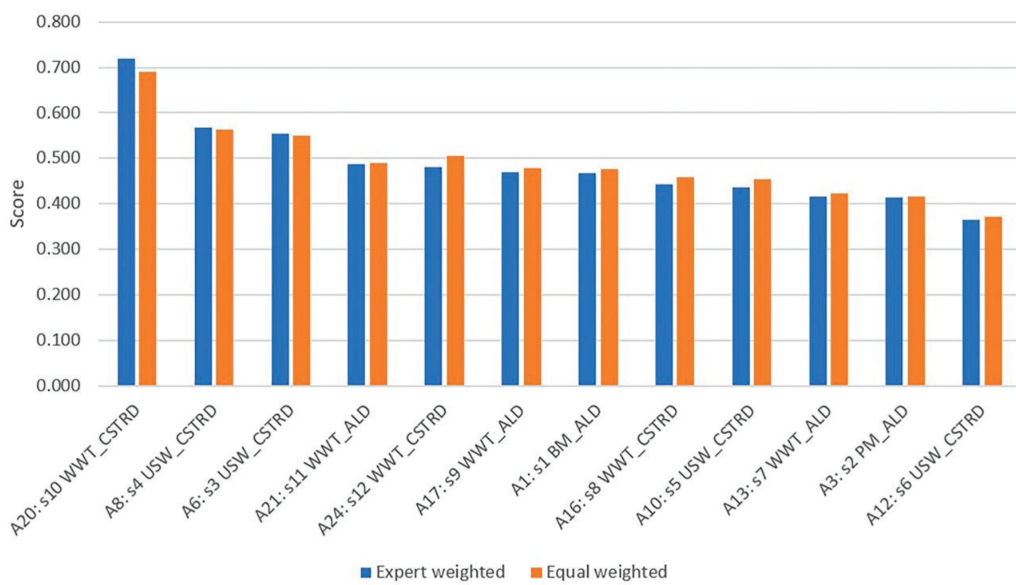

Figure 8: Score sensitivity on weighting factors.

Once the sensitivity analysis has been carried out, the recommendation of this study is to use the results to generate an indicative plan for the use of biomass waste in the BCS region.

5.3. Indicative planning of bioenergy in BCS

A proposal for indicative long-term planning is made from the prioritisation obtained in the SWOT & Fuzzy-logic methodology. The ideal proposal would be to use all the sites with available biomass resources. However, the evaluation reflects sites with low scores. Therefore, it is proposed to carry out a plan prioritizing sites that obtained ratings higher than 0.4, the sites that obtained a lower rating would be discarded.

5.3.1. Progressive implementation of bioenergy in the BCS region

Considering the current planning, a complete characterisation of the plant is necessary. A Bioenergy plant requires at least two years of construction to start operation. The assumption is made that the construction of the first plant will begin in the year 2022, and the period of 2024-2032 will be analysed.

We proposed that starting in 2024, each year, a bioenergy plant will come into operation following the order of priority obtained with the previous analysis, assuming that each bioenergy plant includes a coupled system of a biodigester and a power generation plant. Each site would house a bioenergy plant.

For the plants' design, it is taken into consideration that the waste that exists in each site will increase in the course of time, considering an average annual growth rate (AAGR) depending on where the waste is generated from each site. The AAGR data for the municipalities are: Comondú 1.5%, Mulegé 0.5%, La Paz 1.7%, Los Cabos 3.2% and Loreto 2.6% [50].

Therefore, the design capacity of each plant is selected in such a way that the excessed waste that could be generated in the region can be totally used up in 5 years after starting its operation. It should be remembered that the amount of waste used in the SWOT & Fuzzy-Logic methodology is based on information from the year 2020. Some of the parameters necessary for the evaluation were calculated from this information. Table 6 shows the most critical plant design parameters at each site. The plants are designed to operate for 25 years.

Once the technical parameters are obtained, a calculation is made for the Levelized Cost of Energy (LCOE) for each plant. The plants' costs in USD were obtained using the biogas tool [48] for investment, operation, and maintenance. For this case, the fuel cost is already associated with operation and maintenance costs (O&M). The economical parameters of each plant are presented in Table 7 with the following assumptions: a constant capacity factor depending on the site, a discount rate of 8% [53], an escalation rate of 3% and the use of the cost of electricity for the study region of 0.10 USD/KWh [54] with data from the Federal Electricity Commission (CFE) which is the National Electricity Utility of Mexico.

Starting from the design of the plants, the analysis of the participation of the bioenergy plants in the region is carried out. The plants will not work at their maximum capacity from the year they start operations since they depend on the amount of waste processed.

Figure 9 shows the capacity evolution of bioenergy planning in BCS. It can be observed that by 2032 there could be 9.9 MW of installed capacity with bioenergy.

The total annual generation that bioenergy would produce is shown in Figure 10 and is compared with the demand of the BCS region according to the indicative planning carried out by PRODESEN [10]. It can be observed that by the year 2032, 61% of the energy demand of BCS could be covered by bioenergy.

Table 6: Design parameters of the plants at each site

Site	[a] Daily residue tons (t/d)	[b,1]Methane (m^3 CH_4/h)	[c]Biogas (m^3 /h)	[d]Capacity factor	[e,2]Generation (GWh/y)	[f] Capacity (MW)
s10 WWT	750.32	674.04	1,078.46	0.75	15.89	2.42
s4 USW	147.12	529.26	875.53	0.78	12.98	1.90
s3 USW	166.44	598.74	990.48	0.78	14.68	2.15
s11 WWT	439.84	323.28	517.25	0.75	7.62	1.16
s12 WWT	179.22	161.00	257.60	0.75	3.80	0.58
s9 WWT	150.03	110.27	176.43	0.75	2.60	0.40
s1 BM	34.49	122.92	213.77	0.65	2.51	0.44
s8 WWT	90.47	81.27	130.04	0.75	1.92	0.29
s5 USW	45.08	162.17	268.28	0.78	3.98	0.58

The procedures necessary to obtain the design parameters are shown:

[a] Tons per day available applying the municipality's AAGR.

[b] Product obtained by multiplying the daily tons of waste, the average potential of biogas (1 ton = 400 m3 of CH4), volatile solids% and the dry matter contained in the waste%.

[c] Relation between methane production and methane content (depending on the waste).

[d] Capacity factors vary by type of waste and are obtained from IRENA 2020 [51].

[e] Result of multiplying the amount of methane, hours of operation, calorific value and electrical efficiency.

[f] Relationship between generation and hours of operation in the year.

[1] The %SV and %SV values vary depending on the type of waste, the following assumptions were used: % SV-% ST (WWT: 0.7-7, USW: 0.84-24.4, BM: 0.64-55) [52].

[2] Calorific power of methane 36.905 MJ/m^3 which was reported in [52] equivalent to 10.26 KWh/m^3 of methane.

Table 7: Economic parameters in each site.

Site	Investment cost (Million USD)	Capital cost (Thousand USD/kW)	Fixed O&M (Million USD)	Fixed O&M (USD/kW-year)	Variable O&M (Million USD)	Variable O&M (USD/MWh)	[a]LCOE (USDc/kWh)
s10 WWT	10.59	4.38	3.06	1,266	0.35	22.10	27.60
s4 USW	10.38	5.47	1.97	1,037	0.25	18.96	24.50
s3 USW	11.29	5.25	2.21	1,029	0.26	17.60	24.00
s11 WWT	7.69	6.63	0.93	799	0.05	5.93	30.20
s12 WWT	5.58	9.66	1.02	1,769	0.20	52.38	33.00
s9 WWT	3.82	9.65	0.35	894	0.03	11.38	36.60
s1BM	4.39	9.96	0.56	1,271	0.03	12.24	48.30
s8 WWT	3.87	13.27	0.46	1,589	0.15	79.10	51.10
s5 USW	4.71	8.09	0.66	1,142	0.15	38.70	38.80

[a] From the Levelized Cost of Energy Calculator NREL [33] without including the problems with financing and cost degradation.

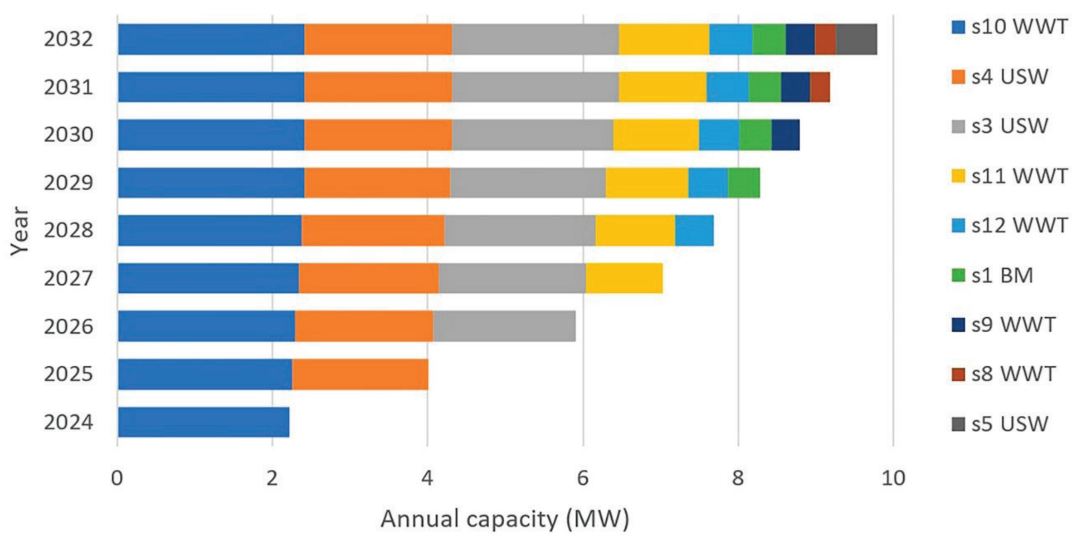

Figure 9: Annual capacity with bioenergy in the period 2024-2032.

Figure 11 shows the annual emissions that each option could avoid in the bioenergy planning proposed for BCS.

The avoided emissions solve an environmental problem in the region and contribute to the reduction of emissions nationally by the simple fact of transforming biomass waste into energy.

According to the results, most of the evaluated sites have deficiencies in some criteria performance. Therefore, for the strategic plan, those sites that obtained a low rating below 0.4 had to be discarded. Despite this, if all the other plants were installed and considering a gradual incursion, 61% of the energy demand in the region could be generated with bioenergy by the year 2032. This would cause positive benefits in the BCS region and, in turn, would reduce emissions, which would contribute to compliance with the country's decarbonization.

From the study carried out and the results obtained, some recommendations arise to the country's public authorities since they regulate the electricity sector in Mexico. Bioenergy must begin to have greater participation in the Mexican electricity sector. The government could strengthen the implementation of policies and mechanisms that support the use of waste for electricity transformation in greater depth. As well as guaranteeing the security and stability of these policies in the long term. It is also recommended to

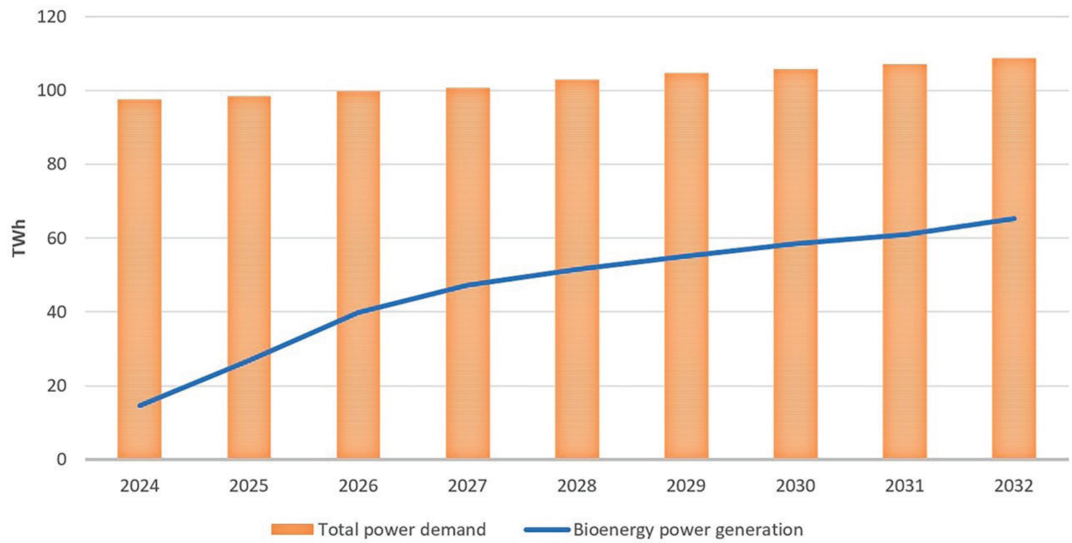

Figure 10: Comparison of annual demand of the BCS region and generation with bioenergy during 2024-2032.

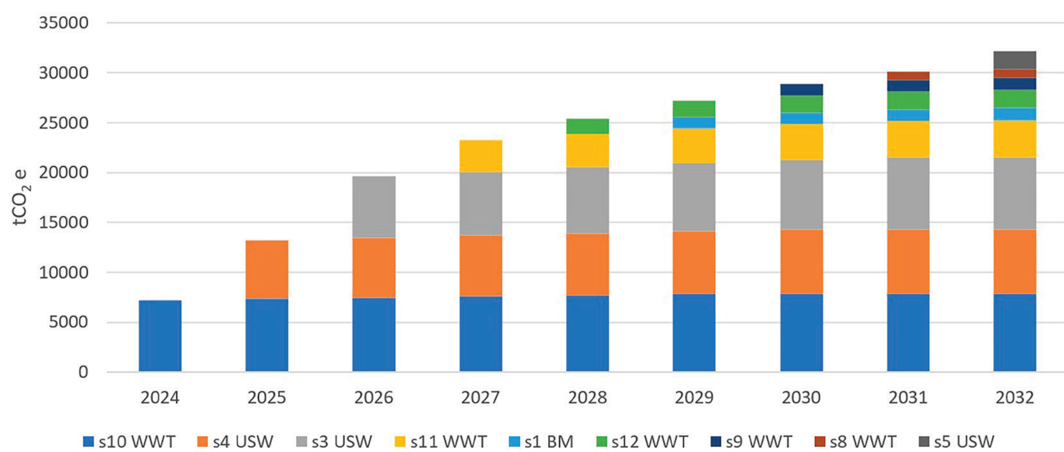

Figure 11: Annual emissions avoided considering the bioenergy plan during the period 2024-2032.

have more incentives that promote lower production costs with high generation efficiencies so that the technology can compete in the market with other renewable energies. Promote projects for distributed generation with bioenergy since the transmission connection weakens the evaluation and generates higher expenses.

6. Conclusions

The proposed SWOT & Fuzzy-logic methodology aims to evaluate the use of biomass waste in sites with high potential for power generation. Following the objective of the research work, it serves as the first reference element to identify the sites in which it is possible to start investing and recognise those criteria to which more attention should be given, such as waste management and technological costs.

The use of methodologies such as the one presented in this study breaks the barrier of implementing decision-making for bioenergy in Mexico, putting into practice a multicriteria hybrid technique that combines SWOT & Fuzzy-logic analysis. With the knowledge and support of experts, the most relevant criteria for this technology could be identified, and diffuse environments were used to obtain a final ranking. The case study is presented to demonstrate the applicability of the proposed framework. Likewise, the sensitivity analysis corroborates that the methodology works appropriately.

Because bioenergy is slightly disadvantaged compared to other clean energy technologies due to its high costs, it is recommended to conduct bioenergy analysis separately and promote the use of all sites for its energy implementation. The indicative plan proposed in this paper may turn out to be an ambitious proposal. However, the bioenergy plants could not be connected directly to the electrical transmission grid and they could be considered for distributed generation to reduce costs of production; this strategy could be applied to those sites with lower ratings.

We demonstrate in this study that bioenergy has the potential to contribute positively to the decarbonisation of the BCS region. It also provides continuous (not intermittent) energy, which generates the security of being able to count on a constant amount of electrical power, which would solve the problems that the region currently has due to the shortage of electricity. Bioenergy solves a social problem since the waste generated can be used instead of dumped in a landfill or into the environment. The country depends less on fossil fuels such as natural gas by generating bioenergy. In addition, it is possible to replicate this analysis for the entire Mexican electricity sector. It is essential to follow up on the indicative plans that may be proposed to promote bioenergy as a long-term electricity generation opportunity.

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Appendix 1

Table A: Information about the expert group

Expert	Designation	Experience	Qualification
E1	Professor	12 years in bioenergy research	PhD
E2	Professor	23 years in energy planning	PhD
E3	Project Manager - Bioenergy Designs	20 years in engineering design	Master's degree
E4	Project Manager – Power, Energy	6 years in energy transition at subnational level analysis	Master's degree
E5	Energy Policy Expert - Sustainability	14 years in energy policies	Master's degree
E6	Policy Energy Expert - Energy planning and sustainability	10 years in a government organization	Bachelor's degree

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