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RESEARCH ARTICLE

A Micro-Wind Turbine Selection Using A Multi-Criteria Method

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ABSTRACT

In this project, a micro-wind turbine was selected that met the characteristics required to satisfy energy demand, using a multi-criteria decision-making method. Using the Analytic Hierarchy Process (AHP) method considering six criteria and five models that met the requirements of the project, and subsequently the selection of a micro-wind turbine. Electricity consumption was characterized in the La Bella farm in a rural area of Acevedo (Huila) municipality, given the maximum wind power potential in the area previously determined, the annual device energy supply was estimated to corroborate the fulfillment of the request. The HF4.0-2000W micro-wind turbine was selected, which will produce 15.31 kWh/day. The micro-wind turbine was selected given its level of importance compared to the other models, being able to meet the energy demand in an additional 4.78% of what is required. Concerning the multicriteria method, the properties of completeness, redundancy, overlap, and independence must be strictly guaranteed to have an acceptable consistency index. The use of the AHP method for decision making is recommended because it allows to the evaluation of different aspects and alternatives among themselves and consolidates all decisions into one.

INTRODUCTION

The use of the wind source in Colombia has been successful, several studies show it. Vera, on the north coast, through WAsP and Windografer software, using field data, proposes to implement a wind farm focusing on technical and financial aspects (Vera González, 2019). Acosta, et al., conducted a feasibility study of wind generation in the city of Tunja based on an energy requirement of 231kWmes per dwelling and propose the use of the E30pro wind turbine of the company Enair, for data collection they were based on meteoblue (Acosta Arcos et al., 2020) (Del Carpio Casani et al., 2018). Quintero, et al., in their technical feasibility study for a wind complex in Huila, relied on data collected by IDEAM, had a statistical approach with an average speed of 6.95 m/s and a reference wind turbine Gamesa g97, and estimated that the project was technically feasible (Quintero Polanco et al., 2016). Other studies include a feasibility analysis of mini-wind generation in Bogotá (Arjona Orozco & Gómez Martínez, 2017), a feasibility study of an offshore wind farm in Coveñas (Duarte Gutierrez & Lopez Olarte, 2020), a feasibility study of wind generation in the Bolívar Canton – Ecuador (Chávez Leones, 2018), a feasibility study of a wind farm in Paracas – Peru (Moreno Diaz & Moreno Begazo, 2017), a feasibility study of a wind turbine in Cayambe - Ecuador (Méndez Cabezas, 2016), a feasibility study of a wind generation system in Tolima (Díaz Caviedes, 2021), and the analysis of properties obtained (Quiroga Bernal, 2017).

In the rural area of the municipality of Acevedo (Huila), in the village of Anayaco, is the farm La Bella, which does not have an electricity supply due to its geographical location, the absence of this service brings difficulties in the activities related to the cultivation of coffee, and with daily needs such as the use of appliances to preserve and prepare food, water pumping, lighting, and even security and entertainment; Access to the national interconnected network requires a lot of investment since the land is not suitable for vehicular access and the passage of the electricity grid is obstructed by trees and private land. Preliminary studies have verified the existence of a usable wind potential in the area in question, making it necessary to study the feasibility of implementing a wind generation system, which requires, in turn, the selection of the ideal technology to implement. For this reason, taking into account the energy requirement and wind speed, information was collected on the models of micro wind turbines available in the market, their characteristics were evaluated using the AHP method according to (Bernal Romero & Niño Sanabria, 2018), and the result was a hierarchy with priorities that showed the global preference for each of the decision alternatives taking into account different criteria that were evaluated and compared with each other.

2. MATERIALS AND METHODS

The geographical location of the project is presented in Figure 1, in the rural area of the municipality of Acevedo (Huila) in the village of Anayaco is the farm La Bella located at coordinates 1 ° 48'46.7 "N 75 ° 52'24.6 "W, in it the minimum energy requirement was determined by interviewing its inhabitants.

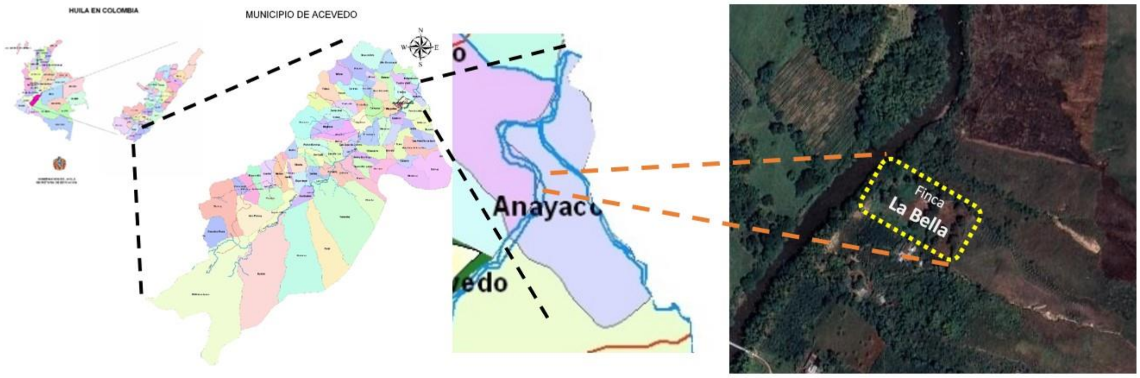

Figure 1:Location of the farm La Bella municipality of Acevedo Huila. Taken using Google Maps. Source: Prepared by the authors.

We opted for a quantitative research approach framed in a non-experimental design where the main variable is the wind speed on the farm and the sample corresponds to the collection of this information over a period of two months, in a previous study the data collected were analyzed using Weibull's law that allowed predicting the behavior of wind speed for a year and determining the frequency with which the different wind speeds are given. Thus, considering into account the energy requirement and wind speed, we proceeded to consult the models of micro-wind turbines available in the market, and established their characteristics, the multicriteria method of support the AHP decision was used to select the ideal technology to implement.

For decision making a process is needed that consists of choosing the best alternative among a set of possible solutions, these are defined from the preferences or desires of each of the decision-makers, in most cases there are limitations in resources that directly affect the restrictions imposed on the decision variables, thanks to this, what is called the feasible or achievable set is constituted. Within the multicriteria decision methods we can find several methodologies; for this case, the method AHP (Analytic Hierarchy Process) was used, which is a method that is based on evaluating and structuring a ranking that allows ordering the alternatives according to their level of importance. The criterion function is known as "utility function" or "value function" and consists of the association of a real number to each feasible solution, which is evaluated and optimized using mathematical techniques. Each of the criteria must be evaluated and compared with each other into stablish a relationship in which a greater, lesser, or equal, value between these criteria is determined; to define this function it is necessary to separate it into two phases, in the first using the technical information what is possible is specified and in the second the judgments of the decision makers define what is better (Bernal Romero & Niño Sanabria, 2018). The AHP method was carried out in seven stages.

2.1. STAGE 1: PROBLEM DEFINITION

The main problem was the selection of the micro-wind turbine because there are different models, with different characteristics, performance, and prices; the research sought to find the best feasible solution based on the different criteria that must be taken into consideration so that decision makers identify the best among all the alternatives.

2.2. STAGE 2: DETERMINE REQUIREMENTS

The requirements that must be met to belong to the group of micro-wind turbines to be selected are: 1. Energy production: the micro-wind turbine must generate more than 380 kWh / month. 2. Environmental conditions: because the area under study is in a tropical climate, it must withstand moderate climatic conditions. 3. Availability: there are different models of micro-wind turbines in the international market, but the import to Colombia of all existing ones is not guaranteed. 4. Weight: The weight of the wind turbine should not exceed 150 kg as it can significantly increase the cost of the structure and freight.

2.3. STAGE 3: DEFINITION OF THE OBJECTIVE

The objective of the researchers when applying the AHP method was to evaluate the alternatives and establish a ranking to obtain weighted scores that qualified each micro-wind turbine and based on these results decide.

2.4. STAGE 4: DEFINITION OF CRITERIA

This stage focused on the designation of the appropriate criteria to evaluate each micro-wind turbine, based on its technical characteristics and aspects of relevance. For the designation of each of the criteria, it was important to respect the following properties: completeness (all the important criteria must be present), redundancy (excluding criteria that due to their similar performance do not contribute to the decision), overlap (avoid double counting) and independence (the performance of one criterion does not interfere with the performance of another); thus the criteria established were: 1. Maximum power: Maximum power that the wind turbine can produce. 2. Output voltage: It directly affects the characteristics of the other components of the wind generation system. 3. Sweep diameter: The wind potential is directly proportional to the sweeping area. 4. Micro-wind turbine weight: Influences tower and freight costs. 5. Starting speed: Establishes the minimum requirement in the wind speed for the operation of the micro-wind turbine. 6. Price: Directly affects economic feasibility and return on investment.

The construction of the hierarchical model makes it necessary to disaggregate the problem among its components until reaching a hierarchical order, for this analysis it was divided into three levels as shown in Figure 2.

2.5. STAGE 5: WEIGHTING OF CRITERIA

The scale of comparison is the axis of decision-making in the AHP method. For this research, a comparison scale was established in Table 1 that was used for the creation of the criteria matrix.

Based on the criteria presented in Stage 4, the level of importance between each of the criteria is evaluated, as reported in Table 2, the criteria column is established as the basis for evaluating the levels of importance;

for example, when selecting from the column "Criteria" the criterion (A) called "Maximum Power" and comparing it with criterion (B) called "Output voltage" it was determined that experience and judgment strongly favor criterion A over B, consequently in the box where they are intercepted the rating 5 is assigned, the second step is to select from the column "Criteria" the criterion "Output voltage" and the box where it is intercepted with the criterion "Maximum Power" is assigned the inverse of the previous rating i.e. 1/5 which is equal to 0.2.

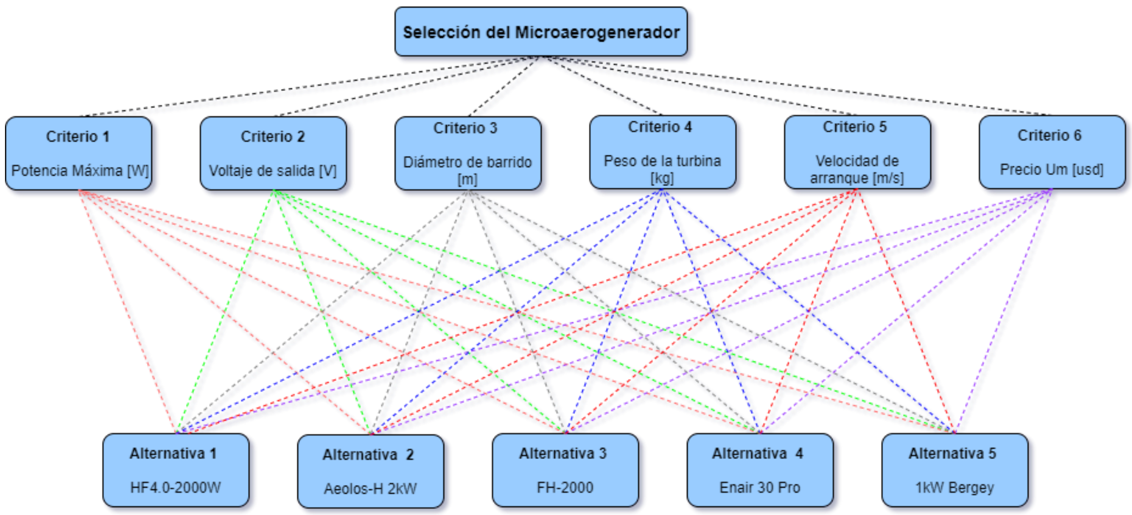

Figure 2: Tree of hierarchies. Source: Prepared by the authors.

Table 1: Paired weighting table. Source: Prepared by the authors.

EQUAL	1	Criterion A is just as important as criterion B.
MODERATE	3	Experience and judgment slightly favor criterion A over criterion B.
STRONG	5	Experience and judgment strongly favor criterion A over criterion B.
VERY STRONG	7	Criterion A is much more important than criterion B.
EXTREME	9	The greater importance of criterion A over criterion B is beyond doubt.

Table 2: Criterion comparison matrix. Source: Prepared by the authors.

Criteria	**Maximum power**	**Output voltage**	**Sweep diameter**	**Turbine weight**	**Startup speed**	**Price**
Maximum power	1,00	5,00	1,00	5,00	3,00	0,33
Output voltage	0,2	1,00	0,20	0,33	3,00	0,20
Sweep diameter	1,00	5,00	1,00	3,00	7,00	1,00
Turbine weight	0,20	3,00	0,33	1,00	3,00	0,33
Startup speed	0,33	0,33	0,14	0,33	1,00	0,14
Price	3,00	5,00	1,00	3,00	7,00	1,00
Total	**5,73**	**19,33**	**3,68**	**12,67**	**24,00**	**3,01**

The procedure for the synthesis of judgment is reflected in the normalized matrix (Table 3) that was obtained from the following steps: you must add the values in each column of the criterion comparison matrix, then divide each element of the criterion comparison matrix by the total of its column. When performing the sum of each row of the normalized matrix e values for the column "Summation" are obtained the weighting is obtained by dividing each element of the column "Summation" by the total of the same column; in this way, it is obtained that the level of importance presented in the last column.

Table 3: Normalized matrix. Source: Prepared by the authors.

Criteria							Sum	Weighting (Wi)	%
Maximum power	0,17	0,26	0,27	0,39	0,13	0,11	1,34	0,22	22%
Output voltage	1,34	0,22	22%	0,03	0,13	0,07	0,36	0,06	6%
Sweep diameter	0,17	0,26	0,27	0,24	0,29	0,33	1,57	0,26	26%
Turbine weight	0,36	0,06	6%	0,08	0,13	0,11	0,60	0,10	10%
Startup speed	0,06	0,02	0,04	0,03	0,04	0,05	0,23	0,04	4%
Price	1,57	0,26	26%	0,24	0,29	0,33	1,91	0,32	32%
Total	1,00	1,00	1,00	1,00	1,00	1,00	6,00	1,00	1,00

After obtaining the results of the criteria matrix, a consistency assessment should be made, which serves to determine if the scores within the criteria comparison matrix were logical. The AHP offers a method for measuring this degree of consistency among the matched opinions that are given by decision-makers; if the degree of consistency is "Acceptable" you can continue with the decision process. The random consistency index "RCI" for this project is 1.24 as six criteria are being evaluated. In Table 4 we proceed to calculate Themb da Max which is the result of making the product sum between the total of the criterion comparison matrix and the column "Weighting (Wi)" of Table 3, and finally the consistency index "CI" and the relationship between the consistency indices "RIC" are calculated; with this result is applied the consistency ratio which states that if the CRP is less than or equal to 0.10 then the consistency is reasonable or acceptable, if the CRP is greater than 0.10 it is inconsistent (Saaty, 1987).

Table 4: Validation of a matrix of criteria. Source: Prepared by the authors.

Lambda Max	∑[(N)(Wi)]	6,53
CI	(Lambda Max-n) /(n-1)	0,106
CRP	CI/RCI	0,085
Valid if	CRP<0,10	Acceptable

2.6. STAGE 6: COMPARISON OF ALTERNATIVES

To evaluate the alternatives, five ranges were first established to categorize the information of each model; for this, the information was used in Table 5 where rank 1 is the most desired and range 5 is the least desired. The second step was to construct the paired weighting table of alternatives (Table 6); where the comparison scale that was used for the creation of the matrix of alternatives was established. Considering Table 6 proceeded to evaluate each of the models according to each criterion for the creation of the matrix of comparison of alternatives, the same procedure was used in Stage 5, but this time comparing the models with each other.

Table 5: Table of ranks. Source: Prepared by the authors.

Rank	**Maximum power [W]**	**Output voltage [V]**	**Sweep diameter [m]**	**Turbine weight [kg]**	**Boot speed [m/s]**	**Price [USD]**
1	3000 to 2500	24	4,5 to 3,9	10 to 50	1,6 to 2,0	$1.000 to $1.999
2	2499 to 2000	48	3,8 to 3,2	51 to 100	2,1 to 2,5	$2.000 to $2.999
3	1999 to 1500	96	3,1 to 2,5	101 to 150	2,6 to 3,0	$3.000 to $4.000
4	1499 to 1000	200	2,4 to 1,8	151 to 200	3,1 to 3,5	$5.000 to $6.000
5	999 to 100	220	1,7 to 1,0	201 to 250	3,6 to 4,0	$7.000 or Elder

Table 6: Paired weighting table of alternatives. Source: Prepared by the authors.

1	Alternative A is in the same range as Alternative B.
3	Alternative A is two spaces in range than alternative B.
5	Alternative A is three spaces in range than alternative B.
7	Alternative A is four spaces away from the range of alternative B.
9	Alternative A is five spaces away from the range of alternative B.

2.7. STAGE 7: UPSHOT

Once all the comparisons were made, the final consensual result was obtained; that is, all the judgments or opinions were combined into a whole by the AHP through the comparisons of each of the criteria and alternatives carried out by the authors and are organized from the best to the worst as will be presented in the results section.

After the application of the AHP method, compliance with requirements by the selected device was verified, for this purpose, the previous wind speed data were used in Equation (1) which allows for determining the power available (P_d) in the airflow, and Equation (2) with which the maximum power (P_{max}) that could be obtained from the micro-wind turbine is calculated.

$$P_d = \tfrac{1}{2}\rho F_e A\langle v\rangle^3 \qquad (1)$$

Where:

ρ: density of air at the site – 1,043 kg/m3.

F_e: energy factor – 1.4.

A: sweep area – $A = 0.25\pi D^2$, where D: is the diameter of the rotor.

$open - angle\langle v\rangle$: average annual speed obtained in the previous study – 5.7 m/s.

$$P_{max} = C_p P_d \qquad (2)$$

Where:

Cp: power coefficient – 0.4 assumed from literature, less than the Betz limit of 0.593.

Still, to make a more accurate calculation, the Weibull probability was used, which, as already mentioned, was used in a previous study to treat wind speed data measured over two months. The results obtained were quite similar.

Finally, a relationship was established between annual energy consumption (AEC) and annual electricity production (AEP), in this way it was possible to calculate to what extent the micro-wind turbine aches cover or not the energy of the farm from the daily energy consumption (DEC) (Letcher, 2017).

$$AEC\ vs\ AEP = \frac{1.15DEC(365\ days)}{AEP} \qquad (3)$$

For the calculation of this ratio, the value of 1.15 was implemented to have a margin of safety of charge and energy necessary to recharge the batteries.

3. RESULTS AND DISCUSSION

3.1. CHARACTERIZATION OF ENERGY CONSUMPTION IN LA BELLA

The main work developed is the cultivation of coffee and fruit trees, to carry out this work requires a coffee pulper moved by an AC motor during harvest time and a motor pump for washing coffee, and an irrigation system in the dry season; Based on the opinion and needs of the inhabitants, the time of use and number of equipment required for daily and productive activities were determined. Table 7 reports the results of the characterization of consumption, as can be seen, a consumption of 12.68 kWh / day which results in a total of 380.31 kWh / month.

Table 7: Table of estimated electricity consumption at La Bella farm. Source: Prepared by the authors.

Dispositive	Consumption (W)	Number of dispositives	Hours of consumption	Wh/day	kWh/day	kWh/mes
Fridge	400	1	16	6400	6,4	192
Light bulb	15	10	5	750	0,75	22,5
Outdoor Lamp	150	2	4	1200	1,2	36
Television	62	1	12	744	0,744	22,32
Motor Pulper	746	1	1	746	0,746	22,38
Cell Phone Charger	5	3	6	90	0,09	2,7
Pump	746	1	2	1492	1,492	44,76
Sound equipment	220	1	5	1100	1,1	33
Blender	350	1	0,1	35	0,035	1,05
Electric Fence	5	1	24	120	0,12	3,6
			Total	12677	12,677	380,31

3.2. MODELS OF MICRO-WIND TURBINES

The use of wind energy is a resource that does not have widespread use in Colombia, however, companies abroad have the technology and make it possible for their products to reach Colombia through importers. For the selection of the micro-wind turbine, five brands were proposed that have the necessary equipment to import their technologies to Colombia: Hengfeng-power, Aeolos Wind Turbine, Flytpower, Enair, and Wattuneed, shipping costs are around 350 dollars. The models were selected considering the electricity demand at the study site and their characteristics are observed in Table 8. After comparison of alternatives developed as described in Stage 6 of the AHP, the results obtained are ordered as shown in Tabla 9 for each of the models and thus the weighting column is obtained, highlighting Model 1 as the best alternative among a set of possible solutions.

Table 8: Technical sheet of micro-wind turbines. Source: Prepared by the authors.

Characteristics	Model 1	Model 2	Model 3	Model 4	Model 5
Company	Hengfeng-Power	AeolosWind Turbine	Flytpower	Enair	Wattuneed
Model	HF4.0-2000W	Alos-H 2kW	FH-2000	Enair 30 pro	1kW Bergey
Origin	China	China	China	Spain	U.S.A.
Rated power [W]	2000	2000	2000	3000	1000
Output power [W]	3000	3000	2100	1900	1300
Output voltage [V]	48/96	96/200	48/220	24/48/220	24/48
Blade quantity	3	3	3	3	3

Blade material	Glass fiber	Glass fiber	Aluminum	Glass fiber	Glass fiber
Rotor diameter [m]	4	4	2	3,8	2,5
Starting wind speed [m/s]	3	2,5	2,5	1,8	3
Survival wind speed [m/s]	8	12	10	11	11
Generator type	3Ph permanent magnetic	3Ph permanent magnetic	3Ph permanent magnetic	3Ph permanent magnetic	3Ph permanent magnetic
Turbine weight [kg]	100	125	188	125	43
Temperature range [°C]	-40 to 80	-20 to 50	-40 to 80	-50 o 60	-40 to 60
Useful life [years]	20	20	20	25	25
Warranty [years]	5	5	5	5	5
Joint price [USD]	1143	3280	3070	11484	11135

Table 9: Table of results. Source: Prepared by the authors.

Model	**Maximum power**	**Output voltage**	**Sweep diameter**	**Turbine weight**	**Boot speed**	**Price**	**Weighting**
1	36%	13%	36%	26%	7%	54%	**0,38**
2	36%	6%	36%	10%	14%	19%	0,25
3	16%	13%	4%	4%	20%	19%	0,13
4	8%	34%	16%	10%	45%	4%	0,12
5	4%	34%	8%	49%	14%	4%	0,12
Weighting of criteria	22%	6%	26%	10%	4%	32%	1,00

3.3. DESCRIPTION OF THE SELECTED MICRO-WIND TURBINE

The selected micro-wind turbine was the HF4.0-2000W model of the Chinese company Hengfeng-Power based on the results obtained by the AHP multicriteria method which after making the paired comparisons and combining them yielded a result that it is the one that represents the best option for the project. The micro-wind turbine is a horizontal axis, three blades or reinforced fiberglass blades, with a sweeping diameter of 4 meters, the direction is done by a weathervane passively, has a three-phase electric generator of permanent magnets and its installation is recommended at a height higher than six meters, these and other characteristics are reported in Table 8, and their power curve is presented in Figure 3.

3.4. CALCULATION OF THE MAXIMUM POWER OF THE STUDY SITE

From the information in the technical sheet, the swept area is calculated, and the power coefficient of the micro-wind turbine is obtained, with these data the maximum power is given by the Equation. With a diameter of 4 m, the sweeping area will be 12.57 m2 and the available power (Equation (1)) of 1601.5 W, so the energy production per hour is 640.6 W on average, however, given the variation of wind speeds according to the time of day this production is not homogeneous, That is to say, that there will be hours with greater production and hours with less production; however, this value serves to forecast the amount of energy that can be produced. To estimate this energy supply, the results obtained by the Weibull probability of late wind speed in a previous study and the power curve of the selected micro-wind turbine are used and thus it was possible to estimate the energy production, as shown in Table 10. To calculate the daily, monthly, and annual energy production it was first necessary to estimate the energy produced in one hour as shown in Table hour either the probability of the wind was used and it was calculated or the maximum power for each wind speed interval; With the product between the wind probability and the maximum power, the net power is obtained, however, this power starts its production from the starting speed of the micro-wind turbine according to the manufacturer.

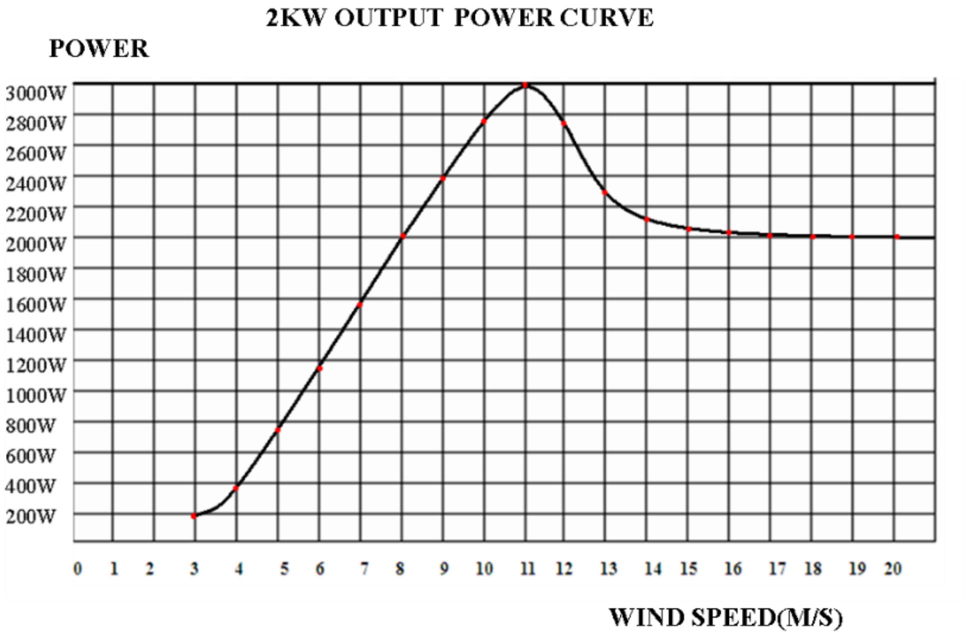

Figure 3: Power curve of the HF4.0-2000W micro-wind turbine. Source: Prepared by the authors.

Table 10: Energy production estimation table. Source: Prepared by the authors.

Wind speed [m/s]	**Maximum power [W]**	**Weibull probability**	**Net power [W]**
0,5	0,33	0,183%	0
1,5	8,84	2,082%	0
2,5	40,94	6,211%	0
3,5	112,35	11,871%	13,337
4,5	238,79	17,205%	41,084
5,5	435,98	19,785%	86,257
6,5	719,64	18,139%	130,532
7,5	1105,50	13,088%	144,694
8,5	1609,28	7,271%	117,007
9,5	2246,71	3,024%	67,951
10,5	3033,50	0,915%	27,758
11,5	3985,38	0,195%	7,786
12,5	5118,07	0,030%	1,521
Total		100%	637,93

It is estimated that energy production will be 15,31 kWh/day, 459,31 kWh/month, and 5588,93 kWh/year, however, being conservative, it is intended to mitigate performance losses and thus guarantee energy production.

3.5. RELATIONSHIP BETWEEN AEC AND AEP

$$CEA\ vs\ EEA = \frac{1.15\left(12.677\frac{kWh}{day}\right)\left(365\frac{day}{year}\right)}{5588.93\frac{kWh}{year}} = 0.9522$$

Since the result is less than one, the ratio indicates that the energy production covers the needs of the farm, and despite the load safety margin of 15% the show can supply an additional 4,78% which does not represent a danger to the system. It should be noted that a result very far from one is not good because if it exceeds a certain threshold, it can negatively affect the equipment and have an excess load, or if it is below, it will not cover the energy needs.

4. CONCLUSIONS

If the micro-wind turbine of the Hengfeng-Power brand corresponding to the reference HF4.0-2000W (model 1) using the AHP multi-criteria method taking into account six criteria and five models that met the requirements of the project, the analysis allowed us to conclude that the micro-wind turbine was selected given its level of importance compared to the other models, being able to meet the energy demand in an additional 4.78% of what is required and will have a production of 15.31 kWh per day.

Concerning the multicriteria method, the properties of completeness, redundancy, overlap, and independence must be strictly guaranteed to have an acceptable consistency index. The use of the AHP method for decision making is recommended because it allows to the evaluation of different aspects and alternatives among themselves and consolidates all decisions into one.

AUTHORS’ CONTRIBUTIONS

VDCC and JCOC developed the Methodology and Decision-Making Process, applying the Analytic Hierarchy Process (AHP) method to evaluate five micro-wind turbine models against six criteria. They selected the device, emphasizing the importance of properties such as completeness, redundancy, overlap, and independence in the multicriteria method. JGAM designed the project and framed the problem, identifying the need for a micro-wind turbine within the context of La Bella farm in Acevedo (Huila), where wind potential had been previously determined. All authors participated in writing and revising the manuscript and approved the final version.

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