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Article

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International Journal of Energy Economics and Policy

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Rojas, Jhan Prieo/García, Gonzalo Romero et. al. (2022). Economic and environmental multiobjective optimization of a hybrid power generation system using solar and wind energy source. In: International Journal of Energy Economics and Policy 12 (1), S. 494 - 499.
https://econjournals.com/index.php/ijeep/article/download/11864/6642.
doi:10.32479/ijeep.11864.

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2022, 12(1), 494-499.

Economic and Environmental Multiobjective Optimization of a Hybrid Power Generation System using Solar and Wind Energy Source

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Received: 01 August 2021 **Accepted:** 11 October 2021 **DOI:** https://doi.org/10.32479/ijeep.11864

ABSTRACT

This article presents a comparison of energy generation using two methods of power production for different geographical locations. For this comparison, the HOMER software was used, which allows simulating generation systems with different energy sources. For the development of these simulations it was necessary to collect three parameters in the locations to be analyzed, which were wind speed, solar radiation and temperature. The photovoltaic array system was simulated using from 10 to 200 units with a constant value of one wind turbine, while for the wind turbine system, 1 to 9 units were used together with a constant value of 100 photovoltaic arrays. For the photovoltaic system, there is no major difference in the net project cost, the renewable fraction and the annual carbon dioxide production when using a greater number of arrays, but an increase in energy production is observed, a greater effect is obtained by changing the location of the system, analyzing the wind system a greater number of turbines increases the energy production, but also increase the annual carbon dioxide production and project cost, there is no significant difference between locations for the project cost the other parameters are affected. By using an optimization algorithm in the systems, the best performance was obtained in Puerto Bolivar using 105 photovoltaic arrays of 1kW and 3 wind turbines of 1.5 MW.

Keywords: Renewable Energies, Solar Energy, Wind Energy, Hybrid Energy System, Multiobjective Optimization
JEL Classification: Q42

1. INTRODUCTION

Currently, the implementation of renewable and competitive energy solutions is desirable in order to generate a transition from traditional energy consumption, especially in the production of energy that involves the generation of greenhouse gases (Capellán-Pérez et al., 2018; Li et al., 2020; Sadiqa et al., 2018). The 2019 technical report of the International Energy Agency projects an increase in electricity generation of 55% by 2040 compared to 2018, where 30% of the increase should be generated by photovoltaic systems and wind turbines (IEA, 2019).

Solar panels and wind turbines can take advantage of solar irradiation and wind speed, respectively, which benefits the Colombian Caribbean region, studies show that only by implementing wind turbines in 20% of the territory of the department of La Guajira and 10% in the sea, the national energy demand of Colombia would be supplied and 40% would be left over (Carvajal-Romo et al., 2019).

Only a little of the potential for electricity production through wind turbines and solar panels in the Colombian Caribbean region is exploited, since fossil fuels are still deeply rooted in the region, in addition to the attempt to implement fracking to extend the use of fossil fuels for a few more years (Strambo and González Espinosa, 2020; Calderón et al., 2016). However, it is likely that in the coming years economic penalties will be associated with the use of fossil fuels and greenhouse gas emissions (Nieves et al., 2019), and the acquisition of solar panels and wind turbines will be more economical and incentivized.

A viable alternative is the implementation of hybrid systems, which would greatly help the adaptation, learning and generation of work for renewable energy systems, while gradually reversing the total operation of traditional fossil fuel systems to systems powered by wind turbines and solar panels (Valencia et al., 2019; Haghighat et al., 2016). Another benefit of implementing electricity generation through renewable energy is that it projects job generation of 16% in the manufacturing industry, 29% in the construction sector, and 50% in operation and maintenance, by the year 2050 (Ram et al., 2020).

This research work is supported using The Hybrid Optimization for Multiple Energy Resources (HOMER) software. HOMER is very useful for the sizing of a hybrid energy supply system since it has the simulation tools to carry out studies with different energy sources, which allows evaluating the performance of power generation plants with one or several renewable sources (Abdul-Wahab et al., 2019). In addition to energy performance, HOMER can provide information from economic and environmental aspects (Al Ghaithi et al., 2017).

Various investigations and technological advances have made it possible to develop methods for obtaining clean energy from multiple renewable sources present throughout the entire globe, among which hydro energy stands out, from which the greatest amount of clean energy is obtained at a level. worldwide, followed by solar and wind energy, and other sources such as the energy present in biomass, geothermal energy, and the energy obtained from the electrolytic process of hydrogen and water; the latter being the most efficient method of all and which is still in the early stages of development. Thus, the main contribution of this article is to present a detailed evaluation of a hybrid power generation system based on technical and economic criteria using real operational data on the Colombian Caribbean coast.

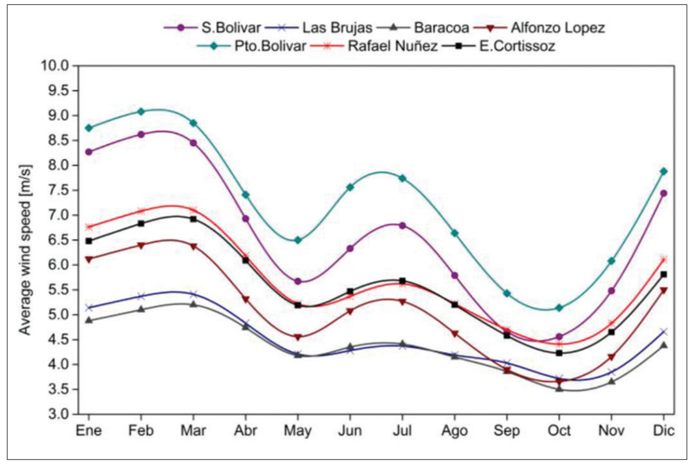
2. METHODOLOGY

2.1. Renewable Energy Resource Data

For the correct development of this research, it was necessary to collect information on three fundamental parameters: Wind speed, solar radiation, and temperature, the values of which are presented in this section. Wind speed is the main resource used by wind turbines to produce electric energy, which is why the different wind speed values, averaged from years of data recording, are presented in Figure 1; it is worth mentioning that the wind speed values have been extracted from the NASA database through HOMER Pro.

The behavior of wind speed as a function of the time of the year can be clearly appreciated for the entire Colombian Caribbean region. During the end and beginning of the year, as well as in its meridian, the wind speed increases, being in the first quarter of the year where the maximum speed is registered. It is also important to highlight that those locations that register less wind speed are the most stable when it comes to the supply of this resource.

Figure 1: Wind speed data for the meteorological stations



2.2. Economy Equations

The main cost analysis in a study reveals the net present cost (NPC) and cost of energy (COE) as a function of the simulated system configurations, the equation for calculating the NPC is described as follows:

$$NPC(\$)=TAC/CRF \tag{1}$$

Where (TAC) is the total annualized cost, and (CRF) is the capital reinstatement factor, which is calculated through the following equation:

$$CRF(\$)=i\cdot(1+i)^{N}/[(1+i)^{N}-1] \tag{2}$$

Where (N) is the number of years and (i) is the real annual interest rate (percentage). The cost of energy (COE), which is the average unit cost per kWh ($/kWh) of electricity produced, is calculated through the following equation:

$$COE(\$/kWh)=C_{tot.ann})/E \tag{3}$$

Where $C_{tot.ann}$ is the total annual cost ($) and ($E$) is the total energy consumed per year (kWh/year).

2.3. TOPSIS Method Equations

Once the Pareto frontier is plotted, it is necessary to determine which of the values are the minimum possible optimal, in this order of ideas, there is a multicriteria decision making method called TOPSIS or technique of preference order by similarity to ideal solution, whose method is applied to select one of the values obtained in the Pareto frontier, considering the closest distance of any value with respect to the lower vertex delimited by both ends of the graph. This technique can be employed by means of the following equation:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_j^+\right)^2}, i = 1, 2, \ldots, m$$
$$d_i^- = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_j^-\right)^2}, i = 1, 2, \ldots, m \quad (4)$$

Where d_i^+ y d_i^- are the distances from any of the points i to the positive and negative ideal solution respectively; t_{ij} is the reference value of alternative i for objective j, whose value is basically the distance from the origin of the graph to the location of point i, t_j^+ and t_j^- are the values for the ideal and non-ideal points respectively, and is nothing more than the distance from these points to the origin of the graph. S_i^+ is the relative distance between point i and the ideal solution, and is calculated using the following equation:

$$S_i^+ = \frac{d_i^-}{\left(d_i^+ + d_i^-\right)} \quad 0 \le S_i^+ \le 1 \quad (5)$$

The best solution is the one closest to 1.

3. RESULTS AND DISCUSSION

For the development of this stage, the simulation will require the capital and replacement costs for the photovoltaic system and the wind system, whose values have been estimated as follows: The 1kW photovoltaic array used in this study will have a unit cost of 3000 $USD, same cost for its replacement; similarly the 1.5MW wind turbines will have a cost of 3,000,000 $USD, same value for its replacement. It should be noted that temperature effects are enabled for this simulation, and costs for alternator modules or other secondary devices are not considered. The annual maintenance and operation costs are defined in Table 1 of this article.

Now that the simulation processes consider both the energy and economic factors, the results are based on case-sensitive optimization processes that help to estimate in which of the two selected locations the system will operate more efficiently. This means that the software will determine through optimization, where the system would make the best use of energy using the least amount of resources possible.

To begin the analysis of the results, it is necessary to clarify that this phase was executed by simulating the systems in two different ways for each of the two locations, where:

1. A system of photovoltaic arrays from 10 to 200 units was simulated, working together with a constant wind turbine value of 1, for both locations
2. A system of wind turbines from 1 to 9 units was simulated, working together with a constant value of photovoltaic arrays of 100 for both locations.

This results in 2 tables of plotted values for the photovoltaic system, as shown in Figure 2, and 2 tables of plotted values for the wind system, as shown in Figure 3.

It can be seen that, regardless of the number of PV arrays, the net present cost of the project does not change substantially, nor does the renewable fraction and carbon dioxide production per year; however, as expected, as the number of PV arrays increases so does the energy production per year. It can also be seen that there are notable differences between the locations compared, since Puerto Bolivar has a higher renewable fraction, a lower net present cost, and a lower carbon dioxide production per year, in all cases compared to its counterpart Simón Bolívar; the same occurs with the annual energy production where, as the number of photovoltaic arrays increases, the difference in favor of Puerto Bolívar is greater.

It can be seen that, as the number of wind turbines increases, the net present cost of the project and the annual energy production also increase; however, the increase in the number of wind turbines

Table 1: Data collected from previous multi-objective optimization

Index	Population *f*1	Population *f*2	*f* (x, y) 1	*f* (x, y) 2
1	125.25	8.00	20.4454	178.4025
2	99.62	1.27	8.6584	406.4433
3	110.83	2.18	9.5129	321.4844
4	101.97	1.03	8.5107	434.1289
5	107.51	1.55	8.8757	376.5218
6	124.68	7.83	20.1269	181.5883
7	114.94	2.75	10.2517	283.3800
8	96.48	1.39	8.7383	394.5251
9	96.14	1.00	8.4941	438.0793
10	111.68	2.29	9.6452	313.2584
11	114.28	5.67	15.6250	203.8996
12	106.53	2.07	9.3843	330.4036
13	117.14	4.23	12.7233	225.1989
14	118.60	6.06	16.4433	200.6926
15	102.08	2.66	10.1158	289.5914
16	115.07	6.07	16.4604	200.7340
17	120.91	7.62	19.7014	185.2911
18	117.31	3.37	11.2079	252.6216
19	114.36	5.49	15.2444	205.5506
20	116.05	1.96	9.2665	338.9139
21	112.22	5.85	15.9893	202.5286
22	117.37	4.06	12.4039	229.5415
23	102.03	2.56	9.9758	296.0198
24	110.51	4.40	13.0414	221.6445
25	107.89	2.09	9.4010	329.1699
26	109.41	2.47	9.8712	300.9298
27	106.31	1.30	8.6807	402.6925
28	116.19	1.89	9.1933	344.8617
29	115.32	2.91	10.4815	274.5616
30	101.74	1.45	8.7887	387.4847
31	112.03	3.92	12.1401	233.8045
32	120.78	4.58	13.3976	217.6507
33	110.91	1.65	8.9627	366.7296
34	105.62	5.30	14.8442	207.7956
35	112.54	4.12	12.5082	228.2153
36	118.03	4.54	13.3151	218.5390
37	98.64	1.48	8.8099	384.8520
38	110.88	6.06	16.4330	200.9517
39	109.20	5.16	14.5614	209.2645
40	113.65	6.36	17.0672	198.6556
41	115.02	6.90	18.2237	194.1354
42	115.53	4.84	13.9231	213.3452
43	117.66	3.66	11.6859	241.8681
44	111.82	7.43	19.2959	188.4046
45	117.46	2.42	9.8108	303.7858
46	117.66	1.99	9.3029	336.0326
47	120.77	6.34	17.0356	198.5679
48	104.99	3.03	10.6530	269.0182
49	113.80	3.18	10.8962	261.1744
50	120.90	7.64	19.7282	185.0817

Figure 2: Top, comparison between the net present cost and the renewable fraction. Bottom, comparison between annual production and estimated annual carbon dioxide production

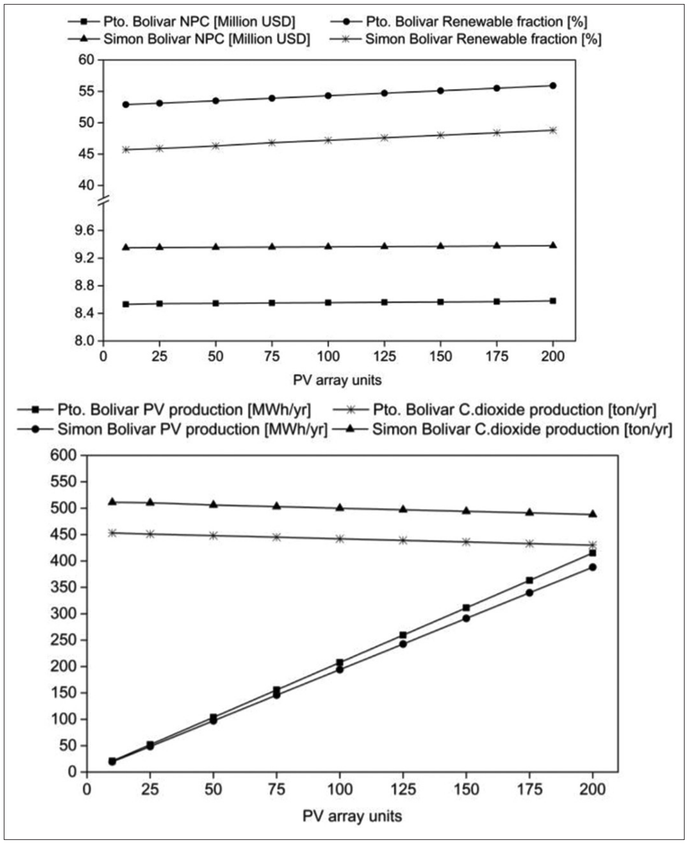
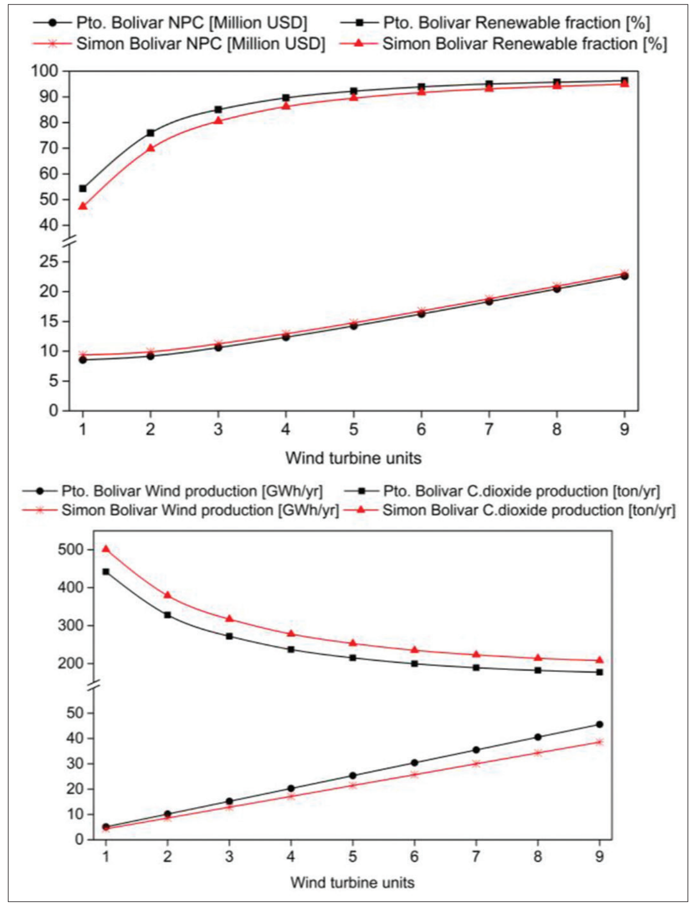


Figure 3: Top, comparison between the net present cost and the renewable fraction. Bottom, comparison between annual production and estimated annual carbon dioxide production



results in a horizontal exponential and asymptotic behavior in the renewable fraction and in the estimated carbon dioxide production per year. It can be seen that, although the net present cost is relatively similar for both locations, there are notable differences in the estimated production of carbon dioxide and energy production per year, in favor of Puerto Bolivar, and likewise it can be seen that Puerto Bolivar has the highest renewable fraction values, although the difference is reduced as the number of wind turbines increases, but without equalizing their values.

Considering the above results, it can be summarized that Puerto Bolivar presents the most favorable conditions for the efficient operation of a wind-solar hybrid system, which is why it is the location that will be considered for the development of phase 3 of this research.

3.1. Third Stage (Multi-Objective Optimization for Puerto Bolívar)

Taking into account that Puerto Bolivar is postulated as the ideal location to implement a wind-solar hybrid generation plant, the next phase consists of determining, through multi-objective optimization processes, the most efficient combination of photovoltaic arrays and wind turbines.

To develop this stage it is necessary to perform an optimization process for Puerto Bolivar, modifying the number of wind turbines from 1 to 8, and the number of photovoltaic arrays from 25 to 200. For this reason, a matrix is developed considering the parameters of net present cost (NTC or NPC) and estimated production of carbon dioxide (CO2), depending on the number of photovoltaic arrays and wind turbines present simultaneously in the system.

Using the curve fitting tool of the MATLAB® software, it is possible to determine an equivalent function for each criterion, NPC and CO2. Figures 4 and 5 show the corresponding polynomial regressions with their respective functions, which are useful for developing multi-objective optimization algorithms in MATLAB®.

$$f(x,y)=8.303-6.436\cdot 10^{-5}\cdot x-0.1896\cdot y+0.0004343\cdot x\cdot y+0.3665\cdot y^2-3.126\cdot 10^{-5}\cdot x\cdot y^2-0.01947\cdot y^3 \quad (6)$$

Where x is the number of photovoltaic arrays and y is the number of wind turbines. This function has an error of 0.02%, likewise, Figure 4 shows the matrix calculated for the NPC criterion, for which it was necessary to establish a third degree polynomial regression to obtain the minimum error.

$$f(x,y)=596.8-0.1401\cdot x-172.6\cdot y+0.03101\cdot x\cdot y+26.24\cdot y^2-0.002224\cdot x\cdot y^2-1.392\cdot y^3 \quad (7)$$

This function has an error of 0.29%, and as can be seen, the percentage error remains below 1%, which means that errors are considered almost negligible when running the multiobjective optimization process. Figure 4 shows the matrix for the estimated

CO2 production, in comparison with Figure 4, the higher the number of wind turbines, the CO_2 production does not change to a great extent, as it does with the NPC.

The next step in the execution of this research consists of developing a MATLAB algorithm capable of being used by means of the Optimtool function to execute the multiobjective optimization process. In that order of ideas and considering the polynomial regressions, the NPC criterion is defined as objective 1 and the CO2 criterion as objective 2. Taking into account that what is desired is to minimize as much as possible both criteria or objectives, a Pareto frontier is required to graphically show the optimal and ideal values considering both objectives and the variations in the number of photovoltaic arrays and wind turbines, as shown in Figure 6.

Figure 4: Polynomial regression for the NPC criterion (Millions of dollars), for Puerto Bolivar

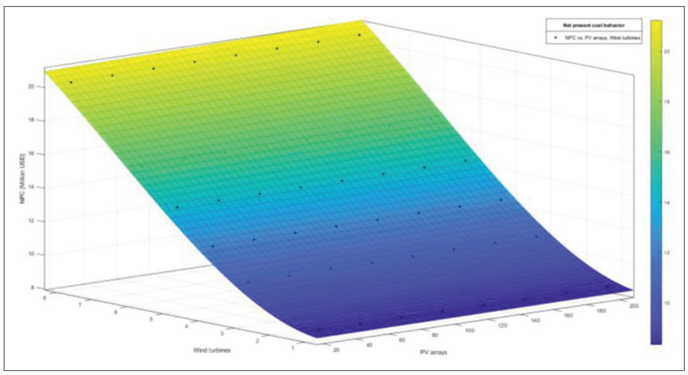


Figure 5: Polynomial regression for the criterion CO_2 (ton/year), for Puerto Bolívar

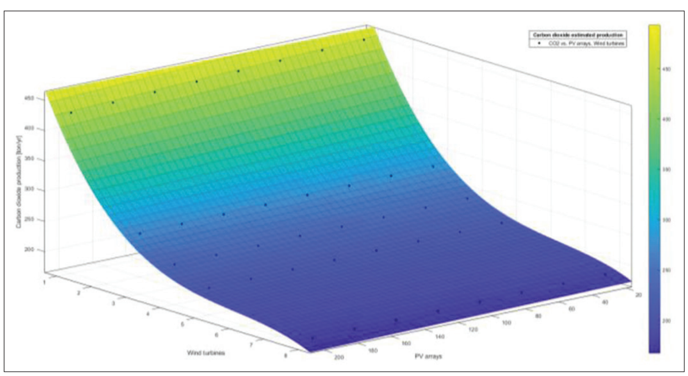
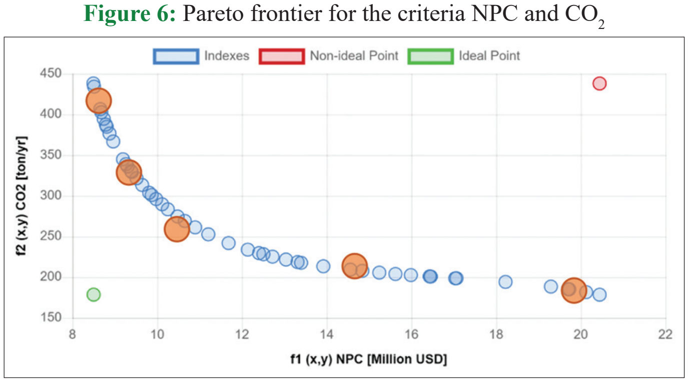


Figure 6: Pareto frontier for the criteria NPC and CO_2



Each value represented in Figure 6 corresponds to a specific combination of number of PV arrays and wind turbines, whose values can be clearly seen in Table 1.

Where populations f1 and f2 are the values for the PV arrays and wind turbines respectively, and f(x,y)1 and f(x,y)2 are the values for the net present cost (million dollars) and estimated CO_2 output (ton/year) respectively.

It is important to note that Table 2 shows values some of which are not feasible, for example, index 45 gives a number of wind turbines of 2.42; but the decimal values are out of range because it is physically impossible to install 2.42 1.5 MW units. The photovoltaic arrays are exempt from this because the number of photovoltaic arrays is very large compared to wind turbines, so it is feasible to approximate these decimal places to the nearest integer.

For this reason, it is necessary to determine which indexes present the values for wind turbines closest to an integer, with less than 0.05 units of difference between them, as shown in Table 2.

It is now necessary to choose one of the values previously shown in Table 2, but it is important to emphasize that all of the above values are the optimal combinations, which means that any selection is the most efficient for your particular combination of wind turbines and PV arrays. Figure 6 then shows these indices projected on the Pareto frontier.

Now it must be determined which of all the feasible solutions shown in Figure 6 and Table 3 is the closest to the ideal solution projected by the Pareto frontier. To achieve this, it is necessary to use the TOPSIS method to calculate the ratio of distances between each of the feasible points with respect to the ideal and non-ideal points of the graph, as shown in Table 3. However, it should be noted that the units of measurement of the two criteria are different, so it is necessary to calculate a S_i^+ for the x-axis and a S_i^+ for the axis y, and then calculate the average of these values to determine which of all of them is closest to 1.

Table 2: Feasible values to consider as an option, obtained from Table 1

Index	PV devices	Wind units	NPC (million USD)	CO_2 production (ton/year)
1	125.25	8.00	20.4454	178.4025
4	101.97	1.03	8.5107	434.1289
9	96.14	1.00	8.4941	438.0793
46	117.66	1.99	9.3029	336.0326
48	104.99	3.03	10.6530	269.0182

Table 3: Feasible values to consider as an option, obtained from Table 2

Index	d_{ix}^+	d_{iy}^+	d_{ix}^-	d_{iy}^-	S_{ix}^+	S_{iY}^+	S
1	11.9504	0	0	259.6768	0	1	0.5
4	0.016	255.7	11.93	3.9504	0.998	0.015	0.506
9	0	259.6	11.95	0	1	0	0.5
46	0.808	157.6	11.14	102.04	0.932	0.393	0.662
48	2.158	90.61	9.791	169.06	0.819	0.651	0.735

From Table 3 it can be seen that, of the values contained in it, index 48 is the one that is closest to 1, which is considered the closest to the ideal solution of the Pareto chart. Considering the above, the ideal system for this case study would operate in Puerto Bolivar, using a total of 105 photovoltaic arrays of 1 kW, and 3 wind turbines of 1.5 MW, with an estimated cost of 10.65 million dollars.

4. CONCLUSION

As the main contribution of this research, study paths are established using software such as HOMER Pro®, MATLAB®, and multiobjective optimization processes through genetic algorithm and TOPSIS method, to determine the energy potential of a particular region depending on the energy demand and the availability of different renewable resources, which in this case correspond to solar energy and wind energy. Likewise, research alternatives are established for meteorological databases and meteorological stations, with the objective of determining the energy potential of a particular region. For the development of the research, three fundamental parameters were selected for each generation system studied, for this case they were wind speed, solar radiation, solar radiation, and solar radiation.

The PV array system was simulated using a range of 10 to 200 units with a constant value of one wind turbine, while for the wind turbine system, 1 to 9 units were used together with a constant value of 100 PV arrays. For the photovoltaic system, there is no major difference in the net cost of the project, the renewable fraction and the annual carbon dioxide production when using a greater number of arrays, but an increase in energy production is observed, a greater effect is obtained by changing the location of the system, for the wind system a greater number of turbines increases the cost of the project and energy production, but affects the annual carbon dioxide production, between locations there is no significant difference in the net cost of the project, the best performance in terms of energy production and carbon dioxide generation is observed in Puerto Bolivar, so it becomes the geographic location selected for the optimization phase of the research shown.

By using an optimization algorithm in the systems, the best performance was obtained in Puerto Bolivar using 105 photovoltaic arrays of 1 kW and 3 wind turbines of 1.5 MW.

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