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Article

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Technical-Economic-Environmental Analysis for the Implementation of Hybrid Energy Systems

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ABSTRACT

In this paper, a technical-economic-environmental analysis was carried out to establish the feasibility of implementing different types of hybrid energy systems. Four hybrid systems (solar-wind) were designed: with battery, with gas generator, grid-connected and with a diesel generator. These systems were analyzed using the hybrid optimization of multiple energy resources software, which allows the calculation of pollutant gas emissions and simulates and optimizes energy consumption based on energy demand and energy resources. For the financial analysis, the net present value, the internal rate of return and the payback period (PBP) were used, which were calculated using Microsoft Excel. The four systems were designed for the energy demand of the luminaires of the academic building of the Universidad del Magdalena. The results obtained show that the first three systems are profitable for their implementation taking into account the capacity of power generation, gas emissions and the PBP.

Keywords: Hybrid Energy System, Environmental Analysis, Financial Analysis
JEL Classifications: Q42, Q51, G00

1. INTRODUCTION

Renewable energies have been partially replacing fossil fuels and nuclear energy in four different markets: electricity generation, thermal applications, transportation fuels and energy services off-grid (Rocas, 2018; Robles et al., 2017). Such is the case of photovoltaic solar energy (PV) and wind energy (Tizgui et al., 2018), which represented a considerable increase in recent years, especially in 2017, where more PV capacity was added than any other type of energy in all the world (Frankfurt School, 2018). PV energy was the main source of new energy capacity in several important markets, such as China, India, Japan and the United States, installing at least 98 GW and increasing total capacity to approximately 402 GW (International Energy Agency, 2018). Worldwide there is an expansion in the market and this is largely due to the growing competitiveness of renewable energy combined with the growing demand for electricity in developing countries, as well as the advantages offered by this type of energy to mitigate pollution (Solar Power Europe, 2017).

Latin America and the Caribbean represent a small portion of global demand, but markets are expanding rapidly and large companies are coming to the region with expectations of higher growth in recent years (Dezem and Chediak, 2018). Brazil became the second country in the region (after Chile) to exceed 1 GW of installed PV capacity, adding almost all of this new capacity in a single year (0.9 GW) for a total of 1.1 GW. With this, Brazil advanced to occupy the tenth global place in aggregate capacity in 2017, although the country represents only about 1% of global additions (Bellini, 2018).

In Colombia, the energy demand of the population has grown considerably in recent years. Only in January 2017 there was a demand of 5428 GWh and in January 2018 the demand was 5619 GWh, presenting an increase of 3.5% (Rojas, 2018). It should be noted that in Colombia the largest source of power generation is hydraulic with 86%, followed by thermal energy that represents 13%, cogeneration with 0.9% and finally are wind and solar energy with 0.1% of installed capacity. These statistics show that the country must incorporate in its energy matrix renewable systems that use non-conventional sources, such as solar PV and wind energy, as well as hybrid systems that take the advantage of the benefits of different types of energy (Revista Dinero, 2018).

In this context it is important to mention that oil, gas and coal are still widely used fuels for the generation of energy. The environmental impact of these energy sources, together with the growth of the population on the planet and its energy demand, has brought harmful effects to the environment. In fact, one objective of the Colombian state is to mitigate the effects of climate change by taking advantage of the potential of available renewable energy resources, which will allow managing the risk of attending to the future demand for electricity. In this way, it seeks to promote sustainable economic development and strengthen regional energy security (Ministerio de Minas y Energía, 2018).

Taking into account the previous scenario, in recent years there has been an increase in research related to hybrid generation systems on-grid and off-grid, using the combination of energy sources such as solar, wind, hydroelectric and generators (Bhandari et al., 2015; Kazem et al., 2017; Ngan and Tan, 2012; Buonomano et al., 2018; Khan et al., 2017; Duman and Güler, 2018; Usman et al., 2018).

For this reason, in this work a technical-economic-environmental analysis was carried out for the implementation of different types of hybrid solar-wind systems that incorporate additional generation sources such as gas and diesel generators. To evaluate the proposed designs, the energy consumption of the luminaires of the academic building of the main campus of the Universidad del Magdalena was used as a case study. It is highlighted as a novelty of this work the incorporation of the environmental component together with the technical and economic aspects to carry out a robust analysis that helps the decision-making for the implementation of energy solutions with hybrid systems.

2. MATERIAL AND METHODS

2.1. Energy Potential

In this section we present a description of the wind, solar and ambient temperature resources that exist in the study area of this work. This information was obtained thanks to the simulation tool hybrid optimization of multiple energy resources (HOMER) (HOMER Energy, 2019), which is connected to the database of National Aeronautics and Space Administration (NASA).

Due to the privileged geographic position of Colombia over Ecuador, the variation of the angle of incidence of the solar rays is very low during the year. This means that PV systems do not require correction of the angle of inclination throughout the year, making operating and maintenance costs lower (Rodriguez et al., 2018).

Figure 1 shows the monthly solar irradiance in the main campus of the Universidad del Magdalena (11.24° N, 74.09° W), where it is observed that the minimum irradiance is presented in November with 5.44 kWh/m^2/day and the maximum irradiance is presented in March with 6.99 kWh/m^2/day.

Figure 2 shows the average monthly wind speed, where it is noted that the minimum speed is presented in the month of October with 4.56 m/s and the maximum speed is presented in February with 8.62 m/s.

Finally, Figure 3 shows the monthly average of the ambient temperature. The minimum value is presented in January with 25.12°C and the maximum value is in July with 26.04°C. It is important to take into account the ambient temperature, since it affects the operation and efficiency of the PV modules, whose maximum efficiency is obtained at an operating temperature of 25°C.

2.2. Energy Demand

The options of hybrid systems proposed in this work were designed for a percentage of energy consumption in the luminaries of the academic building of the Universidad del Magdalena. The four hybrid systems were designed for a load of 6,104 W, which correspond to the consumption of the restaurant, the common areas, the audiovisual room and the administrative area.

In the hours between 10 pm and 6 am the consumption is 30% of the total, that is, 1,832 W. The rest of hours is considered a consumption of 100%, that is, 6,104 W. In this way there is a consumption daily of 112,320 W.

For the sizing of the hybrid system, the HOMER simulation software was used, which allows entering the different electrical

Figure 1: Monthly solar irradiance at the Universidad del Magdalena

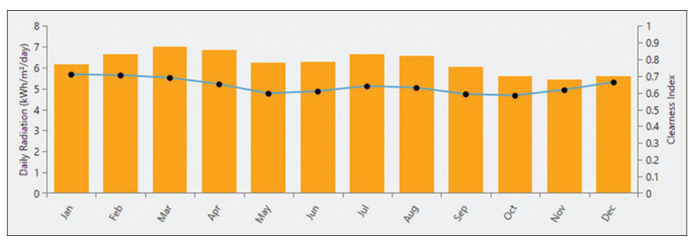


Figure 2: Average monthly wind speed at the Universidad del Magdalena

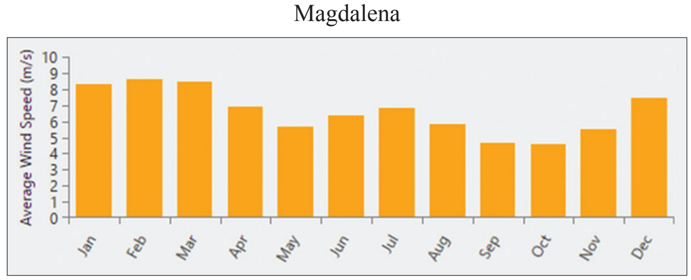
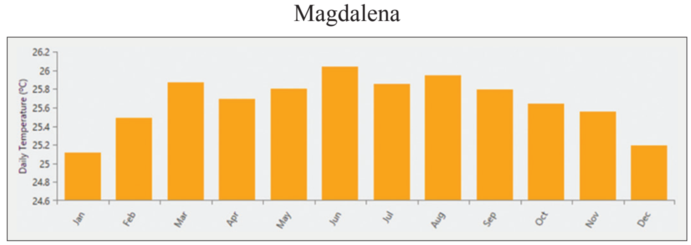


Figure 3: Average monthly ambient temperature at the Universidad del Magdalena



components that will be used for the system to work correctly and automatically performs all possible combinations, taking only those that meet the demand required. Specifically, four hybrid systems options were established:

1. Solar-wind hybrid system with battery
2. Solar-wind hybrid system with gas generator
3. Solar-wind hybrid system with diesel generator
4. Solar-wind hybrid system grid-connected.

The components used for the designs were the following:

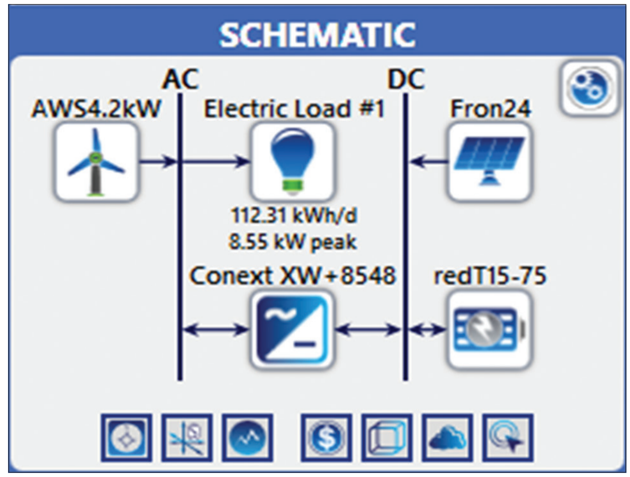
- Polycrystalline module AS-6P of the company Amerisolar, with a nominal power of 330 W, useful life of 25 years, operating temperature between −40°C and 85°C and an efficiency of 17.01%
- For the batteries, a storage machine with a capacity of 75 kWh developed by the redT company was used, which has a nominal voltage of 48 V and a maximum load current of 313 A
- Schneider Electric Conext XW+ 8548 inverter of 7 kW, which has a maximum temperature of 70°C, efficiency of 96% and useful life of 10 years
- AWS HC wind turbine of 4.2 kW, height of 12 m and useful life of 20 years
- For the systems with generators, a generic generator provided by the HOMER software with a capacity of 10 kW was used, but modified to deliver 2 kW with emissions of 16.5 g/m^3.

2.3. Solar-Wind Hybrid System with Battery

This system was designed so that the PV modules generate 70% of the energy during the day and the wind turbine generates 30% of the remaining energy. In the intervals of 6 pm-6 am the PV modules generate minimum energy, while in the intervals of 6 am-9 am and 3 pm to 6 pm, the solar irradiance is not sufficient for the modules to operate at high efficiency.

Therefore, it is necessary that the grid is powered by the energy stored in the battery when the energy produced by the hybrid system is not sufficient to energize the load. The wind turbine will be partially operating 24 h a day, because in the range of 9 am-3 pm the solar irradiance is very high, so the PV modules will be producing their maximum power. Figure 4 shows the block diagram implemented in Homer for this system.

Figure 4: Block diagram of hybrid system with battery



To calculate the power and quantity of PV modules that will be necessary for the system to function correctly, the time intervals described and the total power required by the loads and the battery were taken into account. 70% of this power will be supplied by the PV modules, that is, 78,624 Wh.

The region where the Universidad del Magdalena is located is privileged in terms of solar irradiance, with a maximum value of 6,990 kWh/m^2/day for the month of March and a minimum of 5,440 kWh/m^2/day for the month of November (Figure 1). Using the worst case, we took as reference the minimum irradiance and based on this, we obtained a peak sun-hours (PSH) value of 5.44.

Using the 330 W PV modules, with the PSH value of 5.44, the calculation of the energy produced per day was made, as well as the number of modules needed to satisfy the system's demand. In this way, it was obtained that 44 PV modules are needed as shown in Eq. 1.

Table 1: Costs of the hybrid system components with battery

Component	Quantity	Unit value	Total value
PV modules	44	\$169.6	\$7,462
Inverter	1	\$613	\$613
Wind turbine	1	\$5,673	\$5,673
Battery	2	\$5,826.5	\$11,653
Total			\$25,401

$$N_o Modules = 78624\frac{Wh}{d\,a} \times 1795\frac{\frac{Wh}{d\,a}}{panel} = 44 \quad (1)$$

The battery bank was designed for 75,696 *Wh* corresponding to the hours of the day when the PV modules have the lowest efficiency. A range of 18 h was used, with a voltage of 48 *V* and a discharge depth of 50% for the batteries. Taking these criteria into account, a capacity of 3,154 *Ah* for the battery bank was obtained, as shown in Eq. 2.

$$Battery\,capacity = \frac{75696\frac{Wh}{48V}}{0.5} = 3154\,Ah \quad (2)$$

Taking into account the capacity of the battery and with a nominal DC voltage of 48 *V*, the maximum power required by the inverter is 6,104 *W*

The wind turbine was designed to generate 33,696 *W* equivalent to 30% of the energy demanded by the academic building. For this purpose, we worked with an average wind speed of 4.56 m/s, which represents the worst case in the year shown in Figure 2.

As mentioned in section 2.2, in this work we use the AWS HC wind turbine of 4.2 kW. From this, to calculate the power that the wind turbine will generate daily, we use the data shown in Figure 5, in which it can be seen that for a wind speed of 4.5 m/s, the output power must be of 0.52 kW.

Table 2: Cash flow of the hybrid system with battery

Income	Expenses	Cash flow	Current income	Current expenses
$0.00	$25,401.72	$25,401.72	0.00	$25,401.72
$5,713.25	$1,839.93	$3,873.32	$5,489.65	$1,767.92
$5,713.25	$1,839.93	$3,873.32	$5,274.81	$1,698.73
$5,713.25	$1,839.93	$3,873.32	$5,068.38	$1,632.25
$5,713.25	$1,839.93	$3,873.32	$4,870.02	$1,568.37
$5,713.25	$1,839.93	$3,873.32	$4,679.43	$1,506.99
$5,713.25	$1,839.93	$3,873.32	$4,496.29	$1,448.01
$5,713.25	$1,839.93	$3,873.32	$4,320.33	$1,391.34
$5,713.25	$1,839.93	$3,873.32	$4,151.25	$1,336.89
$5,713.25	$1,839.93	$3,873.32	$3,988.78	$1,284.57
$5,713.25	$1,839.93	$3,873.32	$3,832.68	$1,234.30

Figure 5: Power output versus wind speed

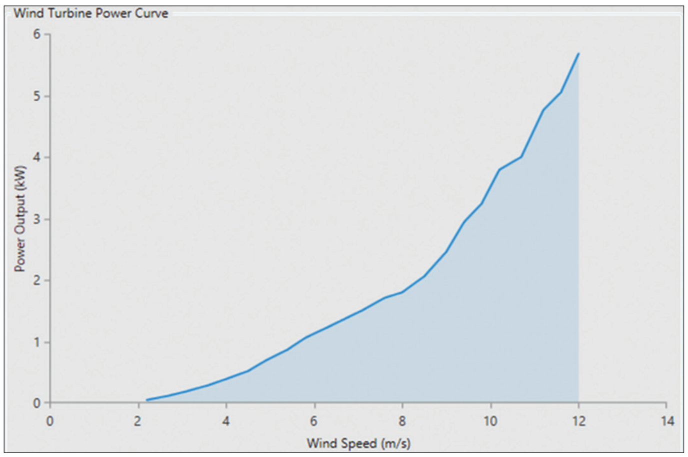
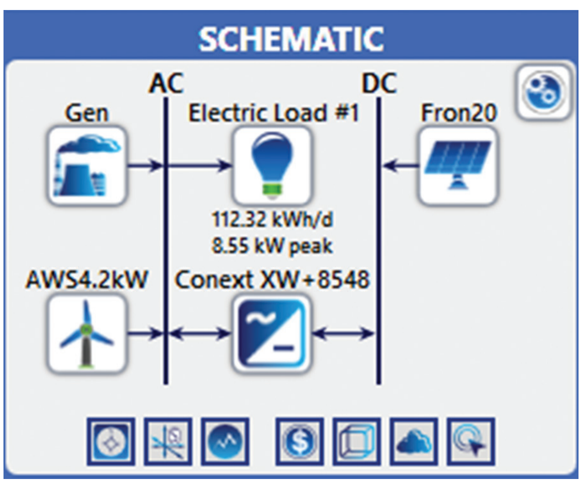


Figure 6: Block diagram of hybrid system with diesel/gas generator



2.4. Solar-Wind Hybrid System with Diesel/Gas Generator

In this case, the design of a solar-wind hybrid system was carried out and two scenarios were proposed as energy backup: the first uses a diesel generator and the second a gas generator.

The PV modules are responsible for generating 70% of the energy during the day and the wind turbine for the remaining 30%. For this purpose, 46 PV modules of 330 W were used in order to generate 14 kW. In addition, the 4.4 kW wind turbine was used to generate the 4 kW corresponding to 30% of the energy demand

Table 3: Indicators of profitability of the hybrid system with battery

Indicator	Value
NPV	$5,900
IRR	9%
PBP	6 years and 7 months

Table 4: Costs of the hybrid system components with gas generator

Component	Quantity	Unit value	Total value
PV modules	44	$169.6	$7,462
Inverter	1	$613	$613
Wind turbine	1	$5,673	$5,673
Gas Generator	1	$634	$634
Total		$0	$14,382

(section 2.3). The wind turbine was configured to operate at a height of 12 m.

For the gas generator, a 2 kW generator was used in order to have an adequate distribution between renewable and conventional energies. This equipment has a density of 0.79 kg/m^3, carbon content of 67%, sulfur content of 0% and a price of 0.3 USD/m^3.

In the case of the diesel generator, a generator with a production of 2 kW was used, which has a density of 820 kg/m^3, carbon content of 88%, sulfur content of 0.4% and a price of 1 USD/L. Figure 6 shows the block diagram for the implementation that was carried out in Homer for the two cases.

2.5. Solar-Wind Hybrid System Grid-Connected

Figure 7 shows the hybrid system grid-connected that was implemented in HOMER. Like the previous systems, this will have the same number of PV modules and the same wind turbine with the same proportions of power generation. The electricity grid provides 15,795 kWh and has environmental parameters of carbon dioxide of 632 g/kWh, sulfur dioxide of 2.74 g/kWh and nitrogen oxide of 1.34 g/kWh. This system will be connected to the local power grid to cover the energy that is not provided by the hybrid system, mainly at night.

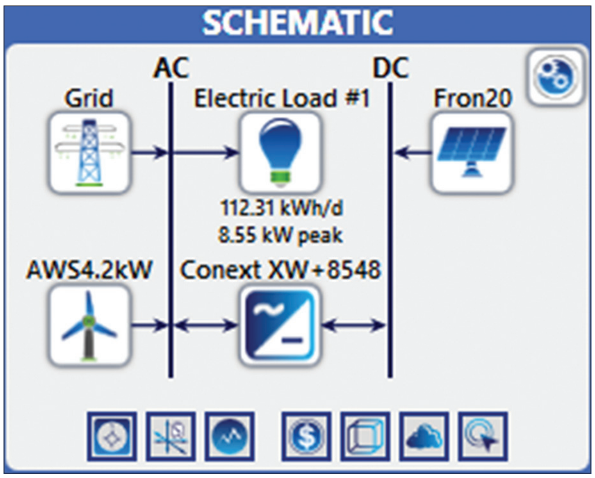
2.6. Environmental Analysis

An environmental analysis of the greenhouse gas emissions emitted by the system was carried out. Since a fundamental part of this study is to determine the CO_2 emissions of each of the four

Table 5: Cash flow of the hybrid system with gas generator

Income	Expenses	Cash flow	Current income	Current expenses
$0.00	$14,382.09	$14,382.09	-	$14,382.09
$7,386.84	$4,423.95	$2,962.89	$7,097.75	$4,250.81
$7,386.84	$4,423.95	$2,962.89	$6,819.98	$4,084.45
$7,386.84	$4,423.95	$2,962.89	$6,553.07	$3,924.61
$7,386.84	$4,423.95	$2,962.89	$6,296.61	$3,771.01
$7,386.84	$4,423.95	$2,962.89	$6,050.18	$3,623.43
$7,386.84	$4,423.95	$2,962.89	$5,813.40	$3,481.62
$7,386.84	$4,423.95	$2,962.89	$5,585.89	$3,345.37
$7,386.84	$4,423.95	$2,962.89	$5,367.28	$3,214.44
$7,386.84	$4,423.95	$2,962.89	$5,157.23	$3,088.64
$7,386.84	$4,423.95	$2,962.89	$4,955.39	$2,967.76

Figure 7: Block diagram of hybrid system grid-connected



cases evaluated, environmental parameters such as fuel density, carbon content and sulfur content will be analyzed. In the case of the grid-connected system, carbon dioxide, sulfur dioxide and nitrogen oxide were taken into account.

2.7. Financial Analysis

Finally, taking into account the data on electricity consumption, energy production, the price of each component, maintenance costs and the necessary economic variables (Castro et al., 2019), we can estimate whether the implementation of the different systems is profitable. For this purpose, the calculation of the net present value (NPV), the internal rate of return (IRR) and the payback period (PBP) was performed, for which Microsoft Excel was used.

The NPV is a method to calculate the present value of an investment, so it is useful to determine if a project is profitable (Eq. 3).

$$NPV = -S_o + \sum_{t=1}^{n} \frac{S_t}{(1+i)^t} \tag{3}$$

Where:
S_t are the expenses, S_o the incomes and n the years.
i is the annual real interest rate.

The real interest rate corresponds to the rate of an asset by subtracting the loss of value of money due to inflation. The value of this rate was obtained by taking the bank reference indicator (IBR) (Banco de la República, 2019), which was developed by the private sector with the support of the Bank of the Republic with the objective of reflecting the liquidity of the Colombian money market. The IBR is a short-term reference interest rate that reflects the price that banks could offer in the money market. For this work the semi-annual nominal rate with a value of 4.073% was used.

Table 6: Indicators of profitability of the hybrid system with gas generator

Indicator	Value
NPV	$9,562
IRR	16%
PBP	4 years and 10 months

The IRR is the rate at which the investment is recovered in a certain number of years, that is, when the NPV is equal to zero. If the IRR is greater than the cost of capital, the project is accepted. If the IRR is less than the cost of capital, the project is rejected.

The PBP is the number of years in which the investment is recovered. It is calculated from Eq. 4 taking into account cash income.

$$PBP = a + [(b-c)/d] \tag{4}$$

Where:
a is the year immediately before the investment is recovered.
b is the initial investment.
c is the sum of the cash flow prior to the year of recovery.
d is the cash flow of the year in which the investment will be recovered.

2.8. Regulatory Framework

In 2014, Law 1715 of 2014 was approved by the Congress of the Republic of Colombia, through which the integration of non-conventional renewable energy into the National Energy System is regulated. The main objective of this law is to encourage investment, research and development of clean technologies for energy production in the national energy system, through its participation in the electricity market, the reduction of greenhouse gases and the security of energy supply (Congreso de la República, 2014).

Due to this law, the development of projects with renewable systems are benefited in economic and functional terms, since

Table 7: Cash flow of the hybrid system with diesel generator

Income	Expenses	Cash flow	Current income	Current expenses
$0.00	$14,382.09	$14,382.09	-	$14,382.09
$7,378.04	$10,387.73	$3,009.69	$7,089.30	$9,981.20
$7,378.04	$10,387.73	$3,009.69	$6,811.85	$9,590.58
$7,378.04	$10,387.73	$3,009.69	$6,545.26	$9,215.24
$7,378.04	$10,387.73	$3,009.69	$6,289.11	$8,854.59
$7,378.04	$10,387.73	$3,009.69	$6,042.98	$8,508.06
$7,378.04	$10,387.73	$3,009.69	$5,806.48	$8,175.09
$7,378.04	$10,387.73	$3,009.69	$5,579.24	$7,855.15
$7,378.04	$10,387.73	$3,009.69	$5,360.89	$7,547.73
$7,378.04	$10,387.73	$3,009.69	$5,151.08	$7,252.34
$7,378.04	$10,387.73	$3,009.69	$4,949.49	$6,968.51

Table 8: Indicators of profitability of the hybrid system with diesel generator

Indicator	Value
NPV	$-38,704
IRR	-
PBP	-

Table 9: Costs of the hybrid system grid-connected

Component	Quantity	Unit value	Total value
PV modules	44	$169.6	$7,462
Inverter	1	$613	$613
Wind turbine	1	$5,673	$5,673
Bidirectional Meter	1	$266	$266
Total		$0	$14,014

the implementation and small-scale connection of new installed capacity is promoted.

Currently, the government issued resolution CREG 030 of 2018, which regulates small-scale self-generation and distributed generation activities in the National Interconnected System. In this same resolution, the maximum power limit is set at 1 MW for a self-generator considered to be a small scale (Comisión de Regulación de Energía y Gas, 2018), defined in Resolution UPME 281 (UPME, 2015).

3. RESULTS

To decide which of the systems evaluated is the most suitable, a comparison was made between them, taking into account electricity generation, the generation of polluting gases and economic profitability. In all systems there will be a fixed saving of 5,657.25 USD which will be taken as income and annual maintenance and operation costs of 1,839.93 USD.

3.1. Hybrid System with Battery

Table 1 shows each of the components that make up this system, which have a total cost of 25,402 USD. With this option, 40,529 kWh/year are produced without CO_2 emissions. Additionally, there will be an additional generation of 405 kWh/year, which generates additional income for 56 USD per year.

Tables 2 and 3 show the cash flow and profitability indicators obtained for this option for a number of periods of 10 years. An IRR of 9% was obtained with a PBP of 6 years and 7 months, which makes this system a profitable option, having the advantage that it does not produce CO_2 emissions.

3.2. Hybrid System with Gas Generator

Table 4 shows the components that make up this system, which have a total cost of 14,382 USD. This system generates CO_2 emissions of 16,701 Kg/year and produces 54,238 kWh/year. Additionally, 59.3% of the energy produced was from renewable sources and the cost per fuel was 2,584.02 USD per year.

In this system, a surplus of energy of 12,533 kWh/year was generated, obtaining additional income of 1,729.59 USD per year. This option will have an additional cost of 2,584.02 USD for the purchase of fuel for the gas generator.

Tables 5 and 6 show the cash flow and profitability indicators obtained for this system. With the IRR of 16% and the PBP of 4 years and 10 months, this system can be classified as a profitable option.

3.3. Hybrid System with Diesel Generator

The costs for this system are the same as those presented in Table 4 for the system that uses the gas generator. With this option, 53,961 kWh/year are generated and CO_2 emissions of 22,851 kg/year are produced. 59.3% of the energy generated was obtained from renewable sources. The cost in fuel is 8,547.8 USD per year.

As with the other options, this system has an energy surplus of 12,247 kWh/year, which produces additional income of 1,690.12 USD. In addition, it is necessary to obtain the fuel necessary for the operation of the diesel generator, with an annual cost of 8,547.8 USD.

Tables 7 and 8 show the results for the financial analysis. Fuel must be purchased in this system as in the system that uses the gas generator, but due to the price of diesel, the investment cannot be recovered.

In addition, the annual expenses produced by the purchase of fuel are greater than the income or savings generated, so it is not a profitable system.

3.4. Hybrid System Grid-Connected

This system generates 52,448 kWh/year and produces CO_2 emissions of 10,081 kg/year. 70% of the energy generated was

Table 10: Cash flow of the hybrid system grid-connected

Income	Expenses	Cash flow	Current income	Current expenses
$0.00	$14,014.11	$-14,014.11	-	$14,014.11
$7,027.09	$4,020.24	$3,006.85	$6,752.08	$3862.90
$7,027.09	$4,020.24	$3,006.85	$6,487.83	$3,711.72
$7,027.09	$4,020.24	$3,006.85	$6,233.92	$3,566.46
$7,027.09	$4,020.24	$3,006.85	$5,989.95	$3,426.89
$7,027.09	$4,020.24	$3,006.85	$5,755.53	$3,292.77
$7,027.09	$4,020.24	$3,006.85	$5,530.28	$3,163.91
$7,027.09	$4,020.24	$3,006.85	$5,313.85	$3,040.08
$7,027.09	$4,020.24	$3,006.85	$5,105.89	$2,921.11
$7,027.09	$4,020.24	$3,006.85	$4,906.06	$2,806.79
$7,027.09	$4,020.24	$3,006.85	$4,714.06	$2,696.94

Table 11: Indicators of profitability of the hybrid system grid-connected

Indicator	Value
NPV	$10,286
IRR	17%
PBP	4 years and 7 months

obtained from renewable sources with an energy cost of 2,215 USD per year. An energy surplus of 9,926 kWh/year was obtained, which generates additional revenues of 1,369.84 USD.

Table 9 shows the components and costs for this option. It should be noted that the energy provided by the conventional electricity grid has an annual cost of 2,180.31 USD.

Tables 10 and 11 show the results obtained for the financial indicators. This system will start producing profits after 4 years and 7 months; due to the monthly expenses derived from the purchase of energy.

4. CONCLUSIONS

Making a comparison between the four hybrid systems from the technical, economic and environmental aspects, the following conclusions can be made.

For the hybrid system with battery we can say that from the environmental point of view, it is the most suitable since it does not generate any type of emission. With this system the least amount of energy is generated and by relying solely on renewable sources, its efficiency is subject to the availability of solar and wind resources. In addition, although this system is economically viable, it is not the most profitable of all the options evaluated.

In the hybrid system with a gas generator, reliability in power generation can be highlighted, although it has an intermediate level of CO_2 emissions. From a technical point of view, this is the option with which more energy is generated. From an economic point of view, this is a viable option, which allows the initial investment to be recovered in <5 years. In addition, with an adequate preventive maintenance plan, income can be generated for 15 years from the payback period.

The hybrid system with diesel generator had the highest CO_2 emissions, and from an economic point of view it was not profitable. Additionally, these characteristics are not compensated for by their power generation, which is not the greatest compared to the other systems.

Finally, there is the hybrid system grid-connected, which stands out as the one with the best profitability and which generates the most energy; although it is not completely renewable and has some CO_2 emissions.

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