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Kontakt/Contact
ZBW – Leibniz-Informationszentrum Wirtschaft/Leibniz Information Centre for Economics
Düsternbrooker Weg 120
24105 Kiel (Germany)
E-Mail: *rights[at]zbw.eu*
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A Hybrid Energy Solution for the Sustainable Electricity Supply of an Irrigation System in a Rural Area of Zona Bananera, Colombia

Juan Camilo Barrera Hernández[1], Christian Moreno[1], Adalberto Ospino-Castro[1]*, Carlos Robles-Algarín[2], Juan Tobón-Perez[1,3]

[1]Universidad de la Costa, Colombia, [2]Universidad del Magdalena, Colombia, [3]Gobernación del Magdalena, Colombia.
*Email: aospino8@cuc.edu.co

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ABSTRACT

A hybrid energy system allows the integration of various technologies to meet energy demands competitively. These systems are widely used in rural areas with connection problems in the conventional electrical grid due to their economic and environmental advantages. Thus, this paper presents the design and simulation of a hybrid energy system that evaluates the suitability of using various generation sources such as photovoltaic energy, biomass, diesel generation and connection to the conventional electrical grid, in order to establish scenarios competitive to supply energy in an irrigation system of the Palmar de la Sierra experimental field, located in the municipality of Zona Bananera, Magdalena, Colombia. The sizing of the system was performed with Homer Pro software, with which technical, economic and environmental aspects of the studied scenarios were evaluated. The data of solar irradiance and the characteristics of the oil palm fruit peel, used for generation with biomass, were provided by the Cenipalma company. The results obtained show that the hybrid system (photovoltaic, biomass, diesel) can satisfy the demand of 2200 kWh/day of the irrigation system under study, using a connection to the electricity grid that allows the purchase and sale of energy.

Keywords: Hybrid Energy System, Photovoltaic Energy, Biomass Gasification, Financial Analysis
JEL Classifications: Q42, G32, G00, O13

1. INTRODUCTION

Electric power is a very important resource for the population, which is why some sectors have considered access to energy as a basic human right (Pelz et al., 2021). The challenge of a modern society is to generate electricity of good quality, low cost and easy to install for all socioeconomic strata. However, there are currently 1.5 billion people (about 22% of the world population) without access to electricity, of which 85% live in rural communities or non-interconnected zones (EIA, 2017).

In Colombia, the most vulnerable populations live in rural areas that comprise the non-interconnected zones (ZNI), where diesel sources, small photovoltaic installations and small hydro power are mainly used to supply their energy needs. Sustainable electrical energy plays a fundamental role in promoting quality services in health, education, and the social well-being of vulnerable communities (Robles-Algarín et al., 2018).

Some studies show that the renewable energy potential in the ZNI is concentrated in biomass, photovoltaic energy and wind energy, with potentials of 16000 MW, 26000 MW and 25000 MW respectively (Eras et al., 2019). The availability of sources such as wind and solar are strongly conditioned by climatic variability, thus in the ZNI these systems are complemented with diesel generators. Considering the economic and environmental costs

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that are caused with these generators, some research indicates that biomass can meet this energy need using gasifying equipment (Asadullah, 2014; Fracaro et al., 2011; Susanto et al., 2018; Susastriawan et al., 2017).

Given the potential that exists in rural areas, the implementation of hybrid energy systems becomes relevant. These systems are characterized by delivering the energy required by the load based on a lower production cost, increasing reliability with the least possible environmental impact (Suresh et al., 2020; Oliveros-Cano et al., 2020). Hybrid renewable energy systems integrated with diesel generators are attractive for their reliability, small-scale application, and for the reduction of greenhouse gas emissions by minimizing diesel consumption (Mohammad Rozali et al., 2016).

For the implementation of hybrid systems, it is necessary to consider technical aspects such as the load, meteorological variations and geographical location, which defines the energy potential that can be used (Lian et al., 2019). The implementation of these systems allows improving the quality of life in rural areas, through the promotion of sustainable development policies, energy efficiency programs and the possibility of attracting foreign investment for national projects (Gallardo et al., 2020; Castro et al., 2019).

In the literature, several studies have been reported that show the importance of hybrid systems in rural areas, which are characterized by being located in ZNI or having poor service from the conventional electricity grid. In research performed by Babatunde et al. (2018), energy efficiency strategies were used to improve the performance of a standalone hybrid energy system. Using Homer software, the authors simulated different architectures of hybrid systems, obtaining that the best solution was the PV/DG/Battery architecture. Similarly, the authors Fakhim and Sarir (2017) used the Energy Plus software to measure the energy consumption of a rural hotel in cold weather. The researchers implemented four hybrid system scenarios with Homer software. The results showed that the ideal architecture for the hotel under study was the wind-diesel hybrid system.

Ali et al. (2021) evaluated the feasibility of a hybrid energy system for rural electrification in a village located in Pakistan. With Homer Pro software, the simulation of the system was performed to meet the peak load demand. Considering the techno-economic aspects, the best solution was obtained with a Photovoltaic/Diesel Generator/Battery system. Furthermore, authors L-Shammari et al. (2021) conducted a feasibility analysis for the implementation of a hybrid system in a rural clinic located in Iraq. In this case, the best option was a hybrid system made up of PV modules, wind turbines, batteries and converters, which was selected considering technical, economic and humanitarian aspects.

In the context of rural housing, hybrid systems also take on relevance. The authors El-Houari et al. (2020) conducted a feasibility study for the implementation of hybrid renewable energy systems in 10 houses of a remote village in Moroccan. Considering technical, economic and environmental aspects, it was found that the best solution was a PV-Wind-Biomass-Battery system.

In farming applications, research has been performed for the implementation of hybrid systems in remote areas (Gbadamosi and Nwulu, 2020). In the same study area, Jayaraman et al. (2019) improved the efficiency of the irrigation system and the yield of crops with the implementation of a hybrid solar microgrid in a rural area of India. Finally, Astatike and Chandrasekar (2019), used Homer to design a hybrid system with wind turbines, solar panels, and a diesel generator. The alternatives were designed to supply reliable and cost-effective electrical power for homes and irrigation systems in a rural area in Ethiopia.

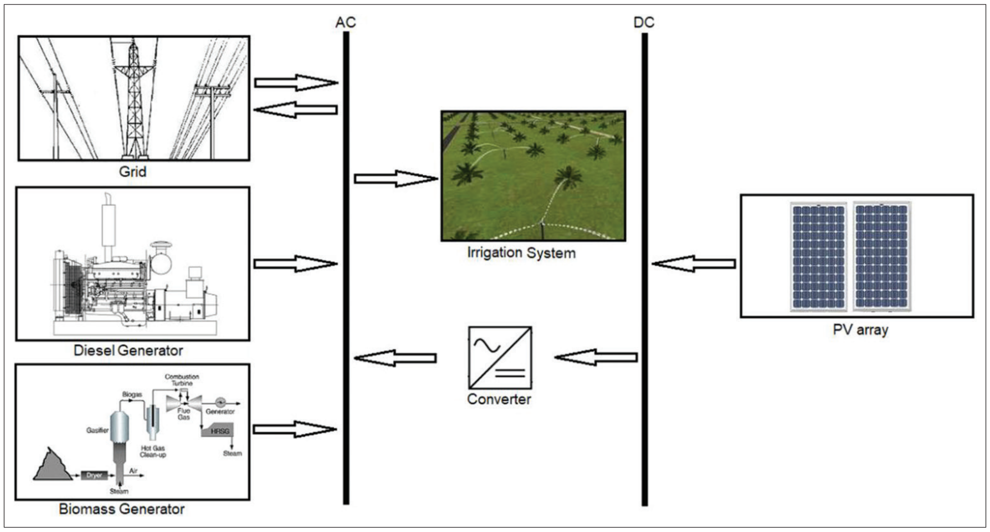
Previous research confirms the importance of modeling different alternatives of hybrid systems applied to rural zones, which regularly have poor access to the conventional electricity grid or are located in ZNI. These areas comprise approximately 51% of the national territory and have an electricity generation capacity of 241 MW, of which only 3% corresponds to non-conventional energy sources (Superservicios, 2018). The highest percentage of energization in the non-interconnected areas is in the departmental and municipal seats, which generally have diesel generators and, in some cases, small hydropower plants. In places with power grid coverage, service is poor and expensive. In general, users of non-interconnected areas pay twice the average per kWh compared to users of the interconnected system, and receive half the hours of service (Esteve, 2011).

In this context, this work presents the design of a hybrid system applied in an agricultural exploitation system in the Departamento del Magdalena, Colombia, which has great potential for the development of agricultural and livestock activities. The generation stage incorporates a photovoltaic system, a biomass gasification system, a diesel generator and a connection to the electricity grid.

2. MATERIALS AND METHODS

The objective of this research is to perform an analysis and design of a hybrid energy system to meet the energy demand of an irrigation system used in farming applications (Figure 1). For the design, energy sources with high energy potential in the region under study were considered: oil palm biomass, PV energy, diesel energy and the electricity grid. The sizing and optimization of the hybrid system was implemented with the Homer Pro software. The performance was evaluated in different settings in order to find the best financial indicators. An optimized system must be economically viable, have environmental benefits, and an attractive pay period. In this way, off-grid and grid-connected scenarios were studied.

Figure 1: Block diagram of the hybrid system



2.1. Study Area

The study area corresponds to the experimental field of Palmar de la Sierra, located in the municipality of Zona Bananera in the Departamento del Magdalena, Colombia (10°43'44.0"N 74°07'08.5"W), which is owned by the Centro de Investigación de Palma de Aceite (Cenipalma) who supported the research with the solar irradiance data of the area. The experimental field has a pumping station with a power of 150 hp, which supplies the water required for the cultivation of oil palm. The area is characterized by being flat with two rainy seasons, the first in April and May, the second in September and November. A season of less intensity of rains occurs between June and August; and finally there is a dry season between December and March (PBOT, 2001).

2.2. Hybrid System Design

At the experimental farm facility, a Fluke 434 series II energy analyzer was used to characterize the energy consumption of the irrigation system (Figure 2). Three types of irrigation are implemented: sprinkler, drip and floodgates, which are used every day from four in the morning to midnight.

Cenipalma has the GeoPalma platform, which incorporates the Agroclimatic Monitoring module (XMAC). This module is a tool that collects, integrates and allows the management of data records from the meteorological station network. From dynamic filters and query panels it is possible to access the meteorological data of each station in real time. The data provided by XMAC are ideal for the development of feasibility studies of PV systems, which allows the integration of a renewable energy source in the oil palm production chain, mainly in applications where there are problems for access to the continuous and quality electrical energy. Figure 3 presents the irradiance profile of the study area registered in the period 2018 - 2019.

Considering the solar potential of the area, high-efficiency solar panels were used in order to obtain the greatest amount of energy available to power the system (Muñoz et al., 2014). The technical characteristics of the panels used are shown in Table 1. According to the energy requirements of the irrigation system and the irradiance profile of the study area, seven (7) solar panels were implemented for the hybrid system.

Figure 2: Load profile of the pump station

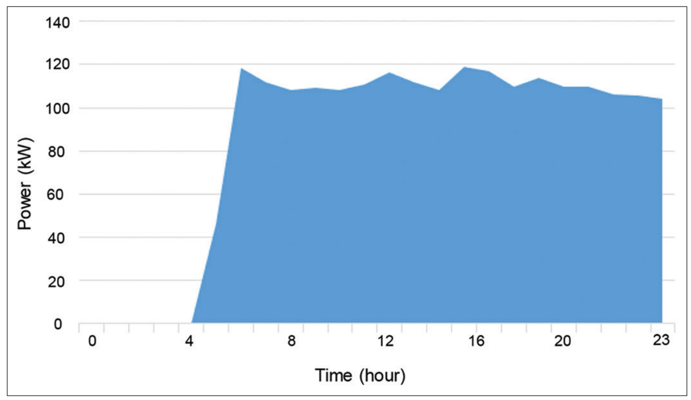


Table 1: Electrical characteristics of the photovoltaic panel (SunPower E20-327-COM)

Electrical characteristics	Value
Nominal Power	327 W
Power Tolerance	+5/3%
Avg. Panel Efficiency	21.4%
Rated Voltage (V_{mpp})	54.7 V
Rated Current (I_{mpp})	5.98 A
Open Circuit Voltage (V_{oc})	64.9 V
Short-Circuit Current (I_{sc})	6.46 A
Max. System Voltage	1000 V Ul and 1000 V IEC
Max. Series Fuse	15 A
Power Temp. Coef.	−0.35%/°C
Voltage Temp. Coef.	−176.6 mV/°C
Current Temp. Coef.	26 mA/°C

For the generation with biomass, the shell of the oil palm fruit was used, which is a by-product with physicochemical characteristics that make it ideal for gasification systems (Bevan Nyakuma et al.,

Figure 3: Profile of solar irradiance for the study area

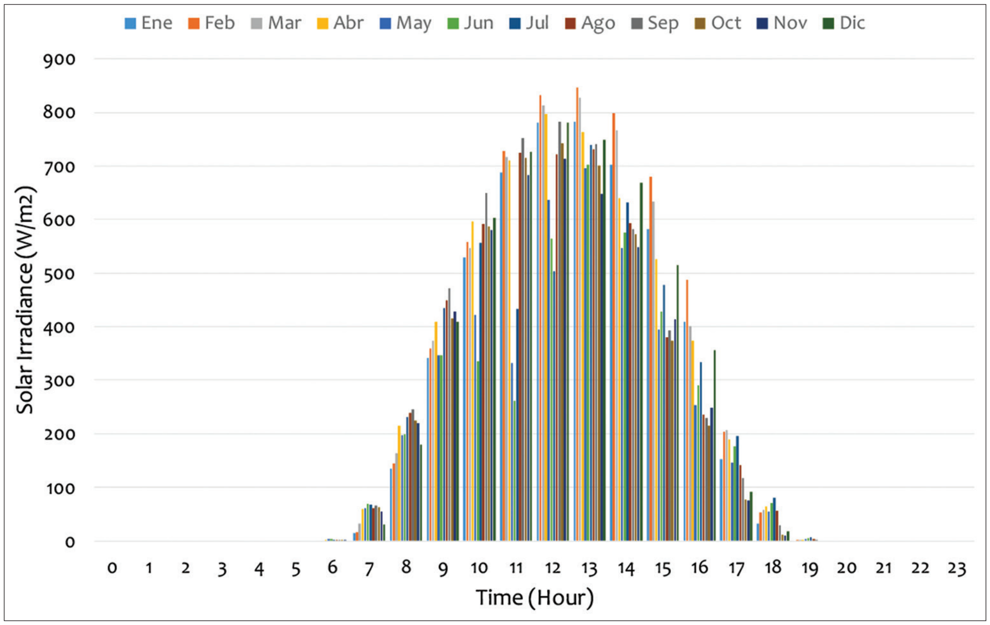


Table 2: Lower heating value, proximate and ultimate analyses of oil palm kernel shells

Ultimate analysis (wt%)					Proximate analysis (wt%)				LHV (KJ/kg)
C	H	O	N	S	M	A	VM	FC	
48.05	6.38	34.10	1.27	0.09	5.4	4.7	71.1	18.8	16.3

C: Carbon, H: Hydrogen, O: Oxygen, N: Nitrogen, S: Sulfur, M: Moisture, A: Ash, VM: Volatile Matter, FC: Fixed carbon, LHV: Lower heating value

2013; Samiran et al., 2016; Ninduangdee and Kuprianov, 2014). Table 2.

The gasification of biomass is a technology used to convert the energy contained in biomass into electrical energy. Gasification thermally degrades biomass by concentrating volatile gases in a synthesis gas (Ranzi et al., 2016). Syngas is captured, filtered, and then burned in gas engines to generate electrical power. For the simulation, a value of $15 USD was used, which includes the sale and transportation values of the biomass (Ramírez et al., 2015). The Gasifier has an electrical efficiency of 20% at full load as described by (Gerssen-Gondelach et al., 2014). The synthesis gas has a calorific value between 4.3 - 4.9 MJ/Nm^3, capital expenditures of $543 USD/kWe and operating expenditures of 6.5% for the fixed cost of the investment (Susanto et al., 2018; Fracaro et al., 2011).

Finally, for diesel generation, the B2/B4 fuel distributed in Colombia was considered, which is a mixture of hydrocarbons 98%/96%. The price of diesel in the country depends on international market prices and the dollar exchange rate. Figure 4 shows a price history from December 2019 to March 2020, where a downward variation in the price of diesel can be observed in March, this due to the beginning of the quarantine in the country and the collapse of the international markets due to the expansion of Covid-19.

Table 3: Diesel generator performance

Frequency	Fuel consumption l/h (gal/h) Load (110%)	Load (100%)	Load (75%)	Load (50%)
50 Hz	35.1 (9.3)	32.4 (8.6)	25.0 (6.6)	16.7 (4.4)
60 Hz	41.6 (11.0)	37.9 (10.0)	29.2 (7.7)	19.9 (5.3)

Thus, a 150 kW Caterpillar DE165E0 generator was used for diesel generation, which has an average cost of between $26,000 - $33,000 USD. A cost per gallon of $2 USD was used, with operating costs equal to 10% of the fixed cost. Finally, using the generator datasheet, the performance of the diesel generator was modeled (Table 3).

3. RESULTS

The hybrid system was simulated with Homer Pro software, for which different configurations were implemented in order to determine the best solution. The dimensions considered were 50 kW, 70 kW, 100 kW and 120 kW, which include the PV system, biomass gasifier and diesel generator; allowing to evaluate the costs and sensitivity of the different options (Figure 5). The design was implemented to meet a peak demand of 2,200 kWh/day with a surplus of 160,000 kWh/year.

The system simulation was initially performed with a diesel generator, gasifier and PV system (Scenario 1). Figure 6 and Table 4 present the costs associated with the system, classified by energy source and the inverter separately. According to the results, the main costs of the system correspond to the purchase of diesel and biomass, representing 52% of the total cost. The project has a net present value (NPV) of $1,030,614.00 USD and the operating costs are 7.8% of the annual NPV (Table 5).

Figure 4: Historical price of diesel per liter in Colombia (USD)

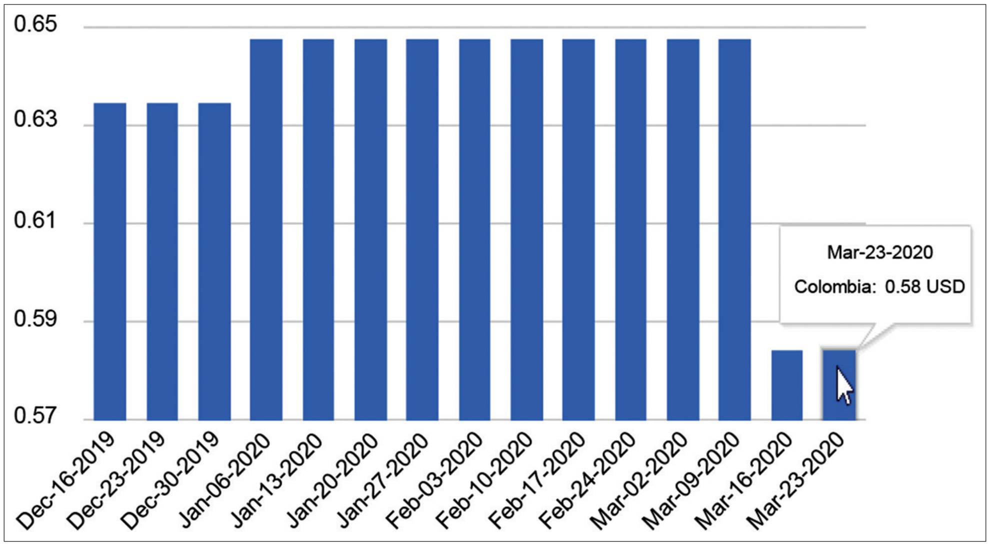


Figure 5: Hybrid system in Homer Pro

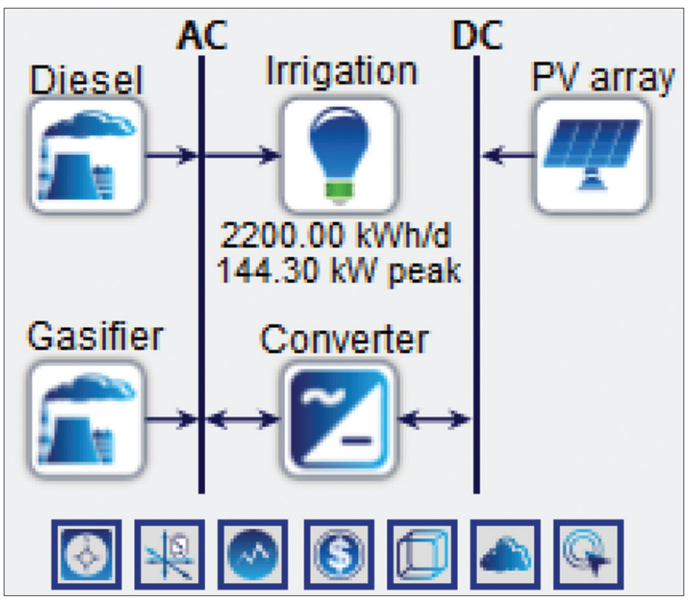


Figure 6: Hybrid system implementation costs for scenario 1 (USD). O and M: operation and maintenance

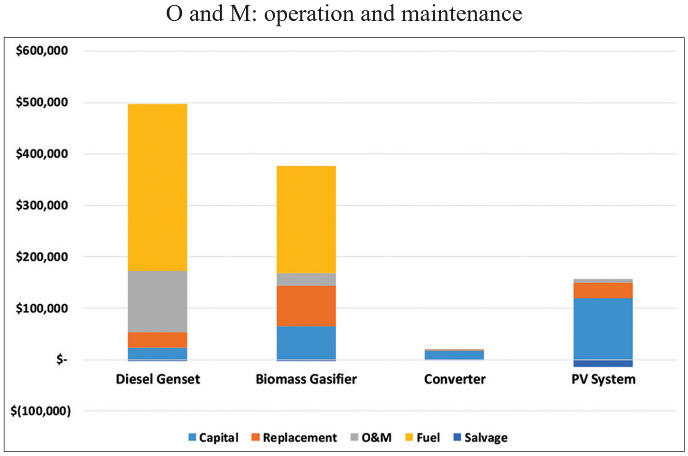


Figure 7: Hybrid system implementation costs for scenario 2 (USD)

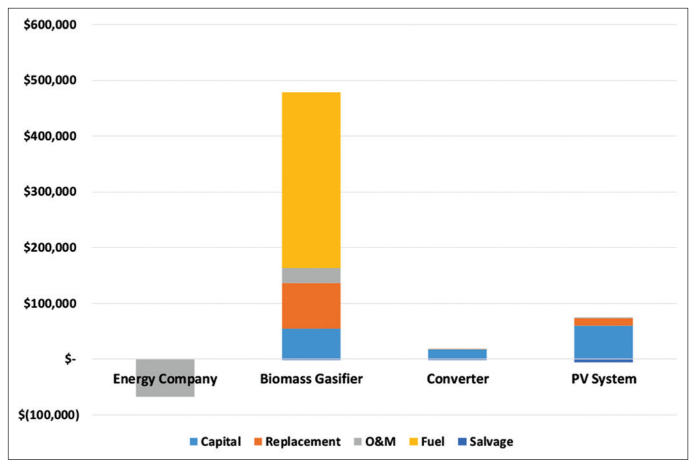
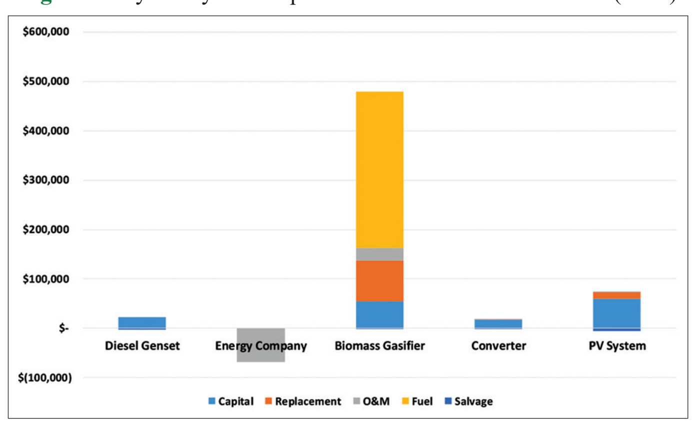


Figure 8: Hybrid system implementation costs for scenario 3 (USD)



Given the high operating costs due to the consumption of diesel used during the nights when irrigation is carried out, a connection to the electricity grid was implemented with the option to purchase surplus energy (Scenario 2). The evaluation was performed in Homer Pro with a purchase value of USD \$12/MWh and a sale of USD \$5/MWh. With this alternative, the need for the diesel plant is avoided by buying energy from the grid and selling the surplus generated by the photovoltaic system (Figure 7 and Table 6). The sale of energy significantly

Figure 9: Energy matrix for the three scenarios implemented

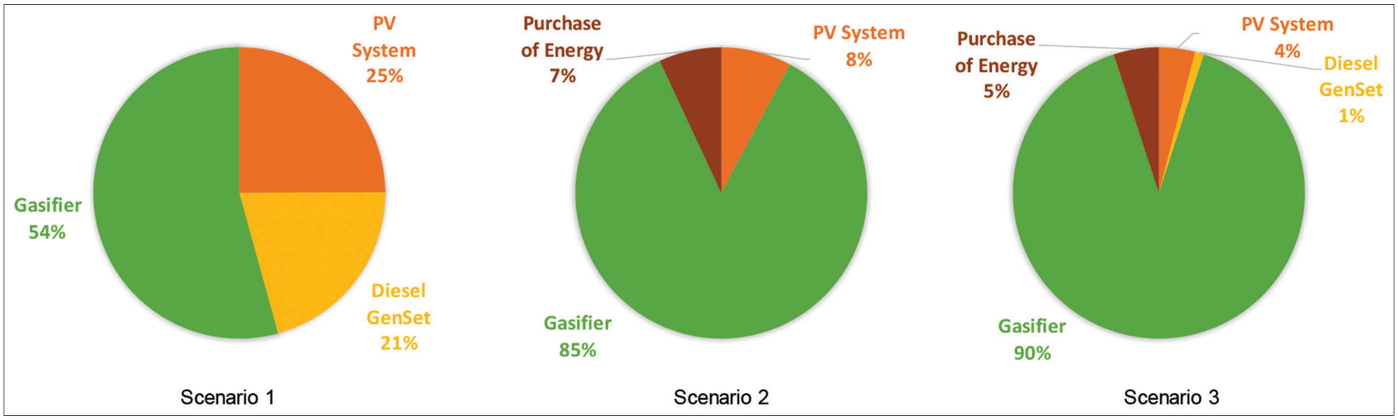


Table 4: Detailed implementation costs for scenario 1

System	Capital	Replacement	O&M	Fuel	Salvage	Total
Diesel genset	$22,517	$30,318	$119,540	$325,289	$-2,434	$495,230
Biomass gasifier	$65,160	$78,127	$24,800	$209,031	$-2,995	$374,123
Converter	$17,800	$688.00	$836	$0	$-314.00	$19,010
PV system	$119,375	$30,608.00	$6,256	$0	$-13,988	$142,251
Total	$224,852	$139,741	$151,432	$534,320	$-19,731	$1,030,614

Table 5: Economic indicators for the scenarios studied

Financial parameters	Scenario 1, Off-grid system (PV, Diesel, Gasifier)	Scenario 2, Grid-connected system (PV, Gasifier, Purchase of Energy)	Scenario 3 (Scenario 2 + Diesel GenSet)
NPV ($USD)	$1,030,620	$495,613	$515,722
LCOE (USD $/kWh)	$0.13	$0.049	$0.051
Operation Costs (USD $/year)	$81,113	$36,678	$36,336

improves the final costs of the project, with a 50% reduction in the NPV and approximately 45% in the operating cost compared to scenario 1 (Table 5).

Finally, a third scenario was implemented, considering the frequent failures of the electricity grid in the rural area under study. The results obtained are shown in Figure 8 and Table 7. In this scenario, an NPV of $515,722 USD was obtained, which is similar to the investment required for scenario 2, but with an increase of 4.1%.

In summary, Table 5 shows the main economic indicators for the three scenarios. In addition, Figure 9 shows the energy matrix for each of the implemented scenarios, and Table 8 shows the greenhouse gas emissions.

4. DISCUSSION

The sizing of hybrid energy systems is presented as a complex task, since due to the variable characteristics of the renewable resources and the load to be satisfied, different challenges arise in the implementation of standardized systems that minimize the number of failures. For this analysis, a great potential for the use of hybrid energy systems is shown, which is evidenced in the results shown in Table 5.

Scenario 1 highlights the use of an off-grid system that guarantees the supply of energy without interruptions and provides environmental benefits in terms of polluting gas emissions. However, in this scenario a strong initial investment is required with high operating costs compared to the other scenarios.

In the case of scenario 2, the decrease in the initial investment and in operating costs is highlighted compared to scenario 1, which is achieved with the connection to the grid and eliminating the diesel generator. This way, this scenario represents a good alternative to supply energy to the irrigation system in the event that there is a stable connection to the electricity grid, which is difficult to guarantee for the rural area under study. For this reason, scenario 3 was considered a viable option since it uses renewable energy sources, connected to the grid and incorporates a backup diesel generator, due to the problems that may arise with the electricity grid. In this scenario, an investment similar to that of scenario 2 is maintained, with a small decrease in operating costs. In addition, as expected, the use of the diesel generator affects the emissions of polluting gases.

In general, the use of biomass resources is highlighted, which are materials that are easily obtained in the field of study of the municipality of Zona Bananera Magdalena-Colombia, a region considered one of the areas with the greatest natural biomass wealth in the Colombian territory. The biomass generation is complemented in an excellent way with the PV generation system, which, due to the strategic positioning of the study area, has great potential with irradiance levels between 5 kWh/m^2 and 5.5 kWh/m^2.

Table 6: Detailed implementation costs for scenario 2

System	Capital	Replacement	O&M	Fuel	Salvage	Total
Energy company	$0	$0	$-68,261	$0	$	$-68,261
Biomass Gasifier	$54,300	$82,466	$26,106	$316,263	$-1,060	$478,075
Converter	$16,953	$655	$797	$0	$-299	$18,106
PV system	$60,000	$12,887	$695	$0	$-5,890	$67,692
Total	$131,253	$96,008	$-40,663	$316,263	$-7,249	$495,612

Table 7: Detailed implementation costs for scenario 3

System	Capital	Replacement	O and M	Fuel	Salvage	Total
Diesel genset	$22,517	$0	$0	$0	$-2,408	$20,109
Energy company	$0	$0	$-68,261	$0	$0	$-68,261
Biomass Gasifier	$54,300	$82,466	$26,106	$316,263	$-1,060	$478,075
Converter	$16,953	$655	$797	$0	$-299	$18,106
PV System	$60,000	$12,887	$695	$0	$-5,890	$67,692
Total	$153,770	$96,009	$-40,663	$316,263	$-9,657	$515,722

Table 8: Greenhouse gas emissions in kg/year

Emissions	Scenario 1	Scenario 2	Scenario 3
Carbon dioxide	167,727	8003	16,060
Carbon monoxide	1560	0	788
Unburned hydrocarbons	45.3	0	0
Particulate matter	26.1	0	29.9
Sulfur dioxide	404	2.74	0
Nitrogen	992	10.34	24.4

5. CONCLUSIONS

After completing this research, it can be concluded that biomass gasification can be considered an excellent alternative to promote hybrid systems in rural areas given the high availability of biomass that exists in Colombia. This technology is still in the early stage of commercial exploitation, therefore, it is necessary to promote the development of projects that adapt to the characteristics of the biomass generated in rural areas.

The hybrid system was successfully simulated in the Homer Pro software, where it was analyzed that the biomass resource in the Palmar de la Sierra experimental field can be used through the gasification process to satisfy a peak demand of 2200 kWh/day. Additionally, the availability of the solar resource in the region, together with the characteristics of the conventional electricity grid in the study area, made it possible to establish that a hybrid system (solar, biomass, diesel, on-grid) encourages the efficient use of the natural resources obtained locally as an optimization alternative to satisfy the energy needs of the proposed irrigation system.

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