Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia

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Electrification to rural and remote areas with limited or no access to grid connection is one of the most challenging issues in developing countries like Colombia. Due to the recent concerns about the global climatic change and diminishing fuel prices, searching for reliable, environmental friendly and renewable energy sources to satisfy the rising electrical energy demand has become vital. This study aims at analyzing the application of photovoltaic (PV) panels, wind turbines and diesel generators in a stand-alone hybrid power generation system for rural electrification in three off-grid villages in Colombia with different climatic characteristics. The areas have been selected according to the "Colombia's development plan 2011e2030 for non-conventional sources of energy". First, different combinations of wind turbine, PV, and diesel generator are modeled and optimized to determine the most energy-efficient and cost-effective configuration for each location. HOMER software has been used to perform a techno-economic feasibility of the proposed hybrid systems, taking into account net present cost, initial capital cost, and cost of energy as economic indicators.

Keywords: Hybrid energy systems, Photovoltaic, Wind, Diesel system, Economic analysis, HOMER

1. Introduction

Energy is considered as one of the central indexes of social and economic development of any country. Nowadays, almost 80% of the global energy demand is met by means of fossil fuels, resulting in significant environmental impacts [1]. Conventionally, electricity is generated in large thermal power plants and is then transported through high-voltage and medium-voltage distribution grids [2,3]. However, greenhouse gas (GHG) emissions, the main source of global warming, as well as the air pollution raise a great deal of concerns mainly caused by continuous burning of fossil fuels for electricity generation [4–6]. On the other hand, rapid depletion of fossil fuel resources on a global scale and progressive increase in energy demand and fuel price are other motives to reduce the reliance on fossil fuels [7]. In order to tackle the aforementioned obstacles related to the conventional power generation methods and cater the present energy demand, the development of power generation systems based on renewable energy is attracting attention as a green solution [8–11].

Renewable energy sources (RES) are virtually so abundant that they can supply more than the global energy demand. They also can be utilized without any cost for the resource [1,3]. Nonetheless, the potential of this clean energy has not been fully exploited due to technical and economic barriers, and the resource availability. During the last few decades, RES have shown growing importance in power generation owing to their emission free, environmental friendly and inexhaustible nature [12,13]. Furthermore, a large proportion of the world's population lives in remote rural areas [2], especially in developing countries like Colombia, and these areas are partially integrated with the electrical grid. This poor electricity distribution is mainly due to geographical inaccessibility, rugged terrains, lack of electrical infrastructure, and high required economic investment for installing large grid connected power lines over long distances to provide electricity for regions with a low population [14,15]. As a result, Distributed Generation (DG) technologies based on renewable energy, called stand-alone hybrid renewable energy system [16,17], can be as suitable options for such remote areas [3,18]. In recent years, owing to the technological improvements and governments' policies to promote RES utilization resulting in significant cost reductions, these units have

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Nomenclature

C	cost (\$)
COE	levelized cost of energy (\$/kWh)
CRF	capital recovery factor (−)
E	energy (kWh/year)
f	energy fraction (−)
i	annual real interest rate (−)
N	system lifetime (year)
NPC	net present cost (\$)
R	remaining cost (\$)
RF	renewable fraction (−)
TAC	total annualized cost (\$)
TOC	total operating cost (\$)
\$	American dollar

Subscripts

ann	annualized
DG	diesel generator
f	fuel
OM	operating and maintenance
R	replacement
S	salvage
tot	total
w	wind

become commercially viable alternatives for electrification in remote areas. In Australia, as an instance, community grants, cost sharing incentives, transition incentives, tax incentives, and environmental markets, are examples of incentives applied on renewable energies [19,20]. In Colombia, the policies include tax exemption or reductions and, till 2013, they were provided by the Ministries of Environment, Housing and Territorial Development, and the DIAN (National Tax Entity) [21]. Since 2014, according to the law 1715, for non-grid access zones, the supporting policies are regulated by the Ministry of Energy and Mines. The policies that have been approved since then include the reductions in the income tax for a period of 5 years, accelerated depreciation of assets, exclusion of VAT (value added tax) on goods related to the project and exemption from customs tariff [22].

However, in contrast to the conventional energy sources, consistency of supply is a significant issue associated with most RES due to their intermittent characteristics under varying atmospheric conditions which considerably influence the resulting energy production [1,4,23]. Consequently, in an effort to overcome the variability of the output of renewable energy systems and to provide a reliable energy supply, which sufficiently meets the demand, renewable energy systems can be combined with non-renewable energy systems and/or energy storage technologies [8,9,24–26]. There has been a vast amount of research on standalone RES and hybrid power systems, which integrate two or more different types of renewable and low carbon technologies (e.g. photovoltaic, wind turbines, fuel cells, diesel generator, etc.). Givler and Lilienthal [27] performed a case study of Sri Lanka in order to compare PV/diesel hybrid and stand-alone solar systems. The study indicated that, as energy demand increases, the PV-diesel hybrid becomes more efficient over single solar technology. Valente and De Almeida [17] performed an economic analysis on hybrid PV/diesel system and demonstrated that over a 20-year period, the hybrid system results in reduction of fuel consumption and operation and maintenance costs, while ameliorating the quality of service. Among various types of RES technologies available on the market, solar and wind energy systems are considered as promising power generating sources due to their availability and topological advantages in remote areas [3,15,28,29]. The intermittent nature of solar and wind resources can be mitigated to a large extent via an optimal integration of these resources to meet the load for extended time periods. The use of solar and wind energy systems are becoming more economically justifiable and technically feasible owing to the manufacturing cost reduction, and extensive research and development in RES exploitation for power generation [3,4,30].

To date, the viability and performance studies of PV systems and PV-based hybrid systems have been investigated in a number of research studies, based on the techno-economic analysis [31,32]. Abdullah et al. [33] stated that hybrid power schemes are more sustainable in terms of supplying electricity to a Tele center in rural area compared to a stand-alone PV system due to lack of solar irradiance. Girma [34]studied a PV/diesel hybrid system where a diesel generator was used as a back-up system in case of scare solar irradiation. The author found that the initial cost of the hybrid system is higher than a stand-alone diesel generator system, while PV covers 95% of the total energy generation of the system. It was concluded that the payback time for the investment cost of the PV/diesel/battery hybrid system is about 2 years, assuming an energy cost of 0.468 \$/kWh.

Moreover, design and control logics of such hybrid systems have been investigated in many works including those dedicated to wind-diesel system using statistical data of loads and wind speed [35], PV-diesel-battery system [36], and solar–wind hybrid power system [37].

Using a photovoltaic/wind/diesel hybrid system can be a more reliable approach for supplying electrical demand of remote areas as compared to photovoltaic-only/wind-only systems [38,39]. This is due to the fact that reliance on a single technology generally results in an over-sizing of the system, thereby increasing the plant initial costs. On the other hand, combining a diesel generator with photovoltaic and/or wind system is to guarantee the minimum diesel fuel consumption and consequently minimizing operating costs and carbon footprint of the system [26,40,41]. Shaadid and Elhadidy [42]studied the techno-economic feasibility of hybrid PV-diesel-battery system for a building with 620 MWh/year energy demand. The system consisted of 80 kW PV and 175 kW diesel with the cost of energy (EC) as 0.149 \$/kWh. Al-Badi [43]evaluated the techno-economic feasibility of running a hybrid wind–PV–diesel power system to satisfy the load of Al Hallaniyat Island.

Nonetheless, due to multiple possible combinations of RES and non-renewable energy sources, as well as dependency on many factors such as the load demand, seasonal availability of energy sources, costs of components and fuel, and governments' policies reaching the best solution is complex and requires to be fully studied [20,40,41]. As a result, several optimization procedures and software have been developed and examined lately to assess the technical and economic potential of various hybrid renewable technologies to simplify the hybrid system design process and maximize the use of the renewable resources. A number of studies aiming at determining the optimal hybrid system for different electrical loads have been reported in the literature [44–48]. In a study by Koutroulis et al. [49], the optimal size of a standalone hybrid system while achieving the least cost using genetic algorithm was conducted and verified the superiority of hybrid solar-wind systems compared to solar/wind single systems. The possible system combinations were characterized by considering some of the system design parameters such as the photovoltaic modules tilt angle, and the wind turbine hub installation height that significantly alter both the installation/maintenance costs and power output [49]. Gu et al. [50] performed an economic examination of a combined heat and power (CHP) system consisting of fuel cells, wind power, PV, heat recovery boiler, and battery by means of a non-linear optimization model. In another study, Kalantar and Mousavi [51]explored the dynamic behavior of a stand-alone hybrid power generation system of PV/wind turbine/battery applying several optimization techniques such as GA, space vector, and fuzzy logic in MATLAB environment.

To meet the renewable energy system sensitivity analysis and optimization needs, HOMER (Hybrid Optimization Model for Electric Renewables) software has been used to perform the techno-economic feasibility of possible configurations. HOMER is an optimization software package, which can handle different technologies (including PV, wind, hydro, fuel cells, and boilers) and evaluate design options for both off-grid and grid-connected power systems for remote, stand-alone, and DG applications. HOMER models each individual system configuration by performing an hourly time-step simulation using inputs such as different technology options, component costs, and resource availability. Then, it investigates technical feasibility of a configuration and estimates the total cost of implementation and operation of the system [52]. Munuswamy et al. [53]compared the cost of electricity from fuel cell-based system and supply from the grid for a rural health center in India, using HOMER simulations. The results revealed that after a distance of 44 km from the grid, cater the electrical demand from an off-grid source is more cost-effective. Lau et al. [15]analyzed a hybrid system for a residential application in Malaysia and applied HOMER to examine the economic viability of the system. Khan and Iqbal [32] conducted a feasibility study for a hybrid system using different renewable and conventional energy solutions and various storage techniques via Homer. Wind-diesel-battery was found as the most feasible solution in their work based on current costs. Shaahid et al. [54] evaluated the technical and economic potential of hybrid wind—PV—diesel power systems to meet electrical energy demand of 15,943 MWh of a remote village, using HOMER software. Dursun et al. [55] studied a micro-grid wind—PV hybrid system for a remote community with 50 houses in order to find the optimal configuration and also represent a techno-economic analysis for the considered power generating systems by the HOMER software. In a similar research, Bekel and Bjorn [28] presented a feasibility study for a stand-alone solar-wind-based hybrid energy system for a model community of 200 families using the HOMER software. Goodbody et al. [24] stated that wind energy was proven to have the highest contribution among RES both for stand-alone and grid-connected systems in Ireland. Recently, Rohani and Nour [56] modeled and optimized a hybrid system consisting of PV, wind, and diesel generator to fulfill different energy demand using HOMER. The results showed that for 500 kW electrical powers, the optimal configuration has 30% and 15% proportion of wind turbine and photovoltaic respectively which leads to a total net present cost of $14,504,952 over 25 years.

To the best knowledge of the authors, there is no comprehensive work on techno-economic evaluation of PV/Wind/Diesel hybrid system in Colombia. As a result, the main purpose of the present study is to analyze three off-grid villages in Colombia with different climatic conditions in order to seek the best combination of available RES to provide electricity demand in a reliable and sustainable manner to each location. First, the solar irradiation, wind speed, and electricity demand were presented for each village to apply the techno-economic analysis, using HOMER software simulation with O&M sensitivity cases. The case study locations have been selected according to the Colombia Development Plan 2011—2030, for non-conventional sources of energy [21] and improve the models using updated data of Colombia Institute of Statistic [57]. In order to determine an optimal design for each location, the initial capital, net present cost (NPC) and cost of energy (COE in $/kWh) have been considered as the main optimization objectives.

2. Description of selected rural regions and the employed components and scenarios

2.1. Location and population

Number of households having access to electricity grid in Colombia has grown from 8 to 12.1 million since 2005 [58], representing nearly 95.8% of the total Colombian population. The remaining 4.2% of the population does not have access to on-grid electricity, while only 26% of them (nearly half a million of people out of two million) have access to alternative energy sources [21]. Many rural areas in Choco, Guajira and Boyaca provinces of Colombia have low level of access to the grid. In these areas, rural electrification growth indexes have increased only by 40% on average. Hence, application of alternative energy sources, such as PV panels, wind turbines and diesel generators, can be a promising option to meet the electrical demand of these areas.

The selected populations are the communities living in the rural areas near the following towns: Uribia (Puerto Estrella zone with a population of 800 inhabitants) in La Guajira state, Unguia (Titumate zone with a population of 430 inhabitants) in Choco state and Jerico (Bácota, Tapias, Juncal, Tintova, Estancia and Ovejera zones with an overall population of 520 inhabitants) in Boyaca state.

It should be noted that the chosen areas correspond to low-income communities without grid connection near these three towns; as an instance Jerico has nearly 4000 inhabitants and is subdivided into 9 zones (Bácota, Tapias, Juncal, Tintova, Estancia, Ovejera, Centro, Chilcal, Cucubal and Puebloviejo); the communities living in the first six zones are considered in this study. According to the development plan of the town [59] 130 houses (520 inhabitants) situated in these six zones do not have access to the grid.

For the sake of simplicity, these communities are called Puerto Estrella, Unguia and Jerico in the following sections.

The data provided by national administrative department of statistics of Colombia (DANE) [57] on the availability of electricity for rural population has been employed. These areas are geographically separated and climatically different but they share similar accessibility issues. The geographical position of the chosen locations is demonstrated in Fig. 1. The geographic and demographic information as well as the climatic characteristics of these locations are presented in Table 1.

2.2. Load estimation

Current population of each location has been obtained from DANE's (National Statistics Administrative Department) database while estimations from Murillo S. J., R.P.C [57], and PDFNCE were used to determine the electricity demand and energy requirements of each community [21]. The major part of electrical load can be attributed to lighting (40 W fluorescent lamps), entertainment (specifically 15 W radios and 100 W television as a community load), and 50 W as a reserve (that can be used for a small low consumption fridge). Wood, coal or gas (tank) fed furnaces are considered to be used for cooking. It is noteworthy that, since the economy of these communities is based on agriculture, the working population is commonly outside the house during the day. Furthermore, two basic services, a health center and a school, with the loads of 1.5 kW and 1.8 kW respectively, have been considered

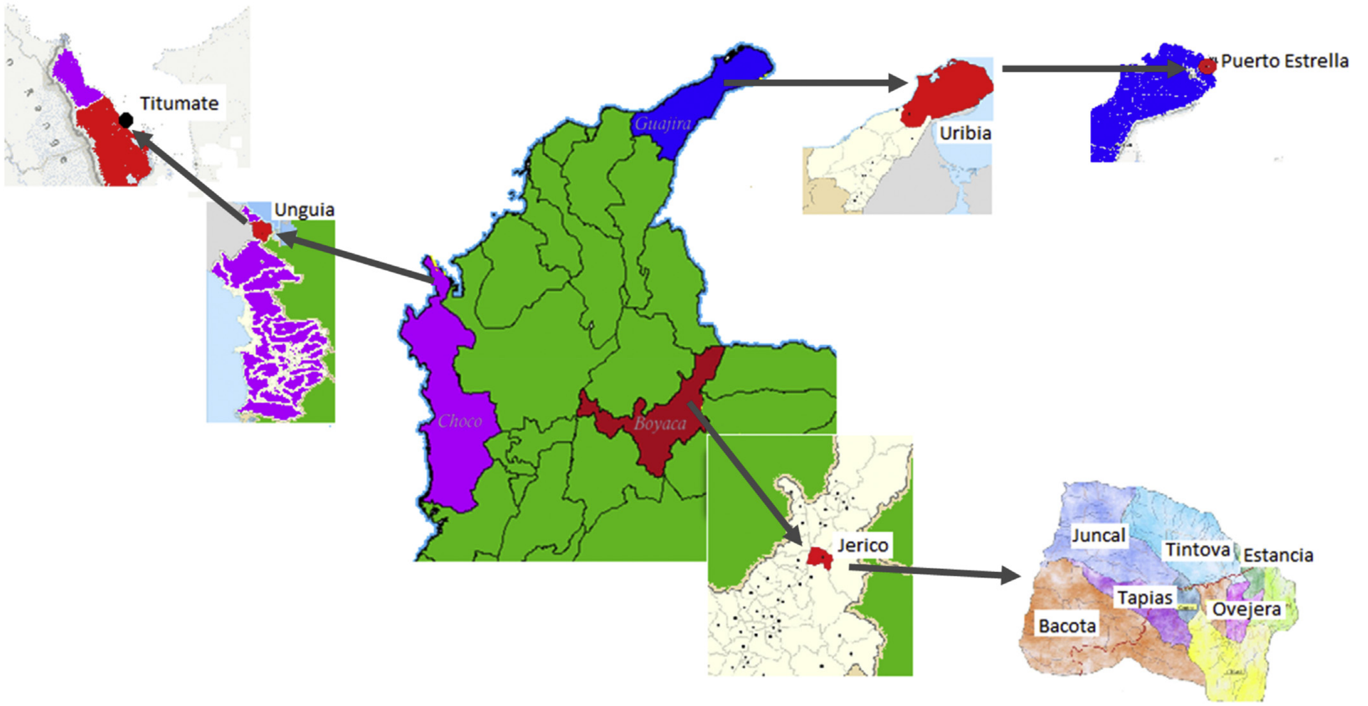


Fig. 1. Geographical position of the considered locations in Colombia.

Table 1
Geographic and demographic information of the selected communities [57,58].

Area		Geography	Climate		Electricity	
Community	Region	Altitude (m)	Precipitation (mm)	Average annual temperature (°C)	Consumption (kWh/d)	Peak load (kW_p)
Puerto Estrella	Guajira	6	100	30	379	88
Unguia (Titimate)	Choco	66	2000	27.5	180	38
Jerico (Rural)	Boyaca	2590	420	12.5	213	41

in the calculation of the load profile for these areas. As recommended by Bekele and Boneya [30], the typical health clinic is considered to be equipped with vaccine refrigerator, light bulbs, stand-by communication VHF radio, microscope, vaporizer, centrifugal nebulizer, oxygen concentrator, ceiling fans and AM/FM radio receiver. Although Puerto Estrella's average temperature is around 30 °C and Unguia's around 27.5 °C, application of air conditioning systems is not considered. The later assumption is due to the fact that air conditioning systems are costly and have a high consumption and accordingly the use of these devices is not common in low-income communities. The hourly electrical load profile during workdays and weekends in Puerto Estrella are shown in Fig. 2. These profiles have been determined in accordance with a guideline presented by Bekele and Boneya [30]. As shown in this figure, the electricity consumption slightly decreases from December to February and in June, which correspond to the end of the academic period and beginning of vacations respectively. Average monthly electricity consumptions for the three communities though the year are shown in Fig. 3.

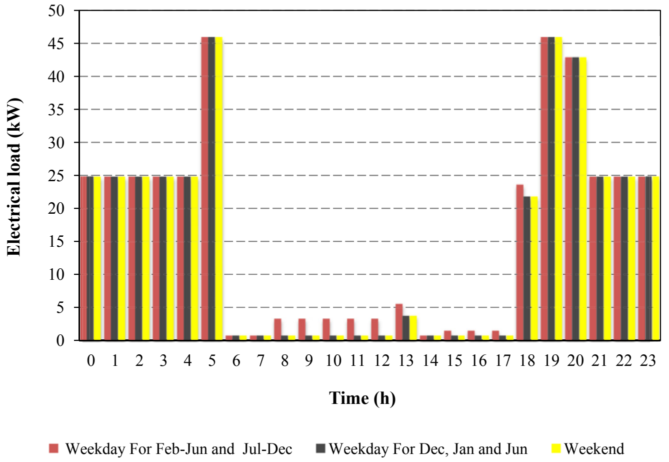


Fig. 2. Daily electrical load profile during weekday and working day for Puerto Estrella.

2.3. Availability of renewable energy resources

Using the solar and wind atlases of Colombia [60,61] and the geographic coordinates as the input information, the average monthly solar radiation and wind speed for the considered locations are determined and demonstrated in Fig. 4a and b respectively. Furthermore, in order to acquire an accurate estimation of the accessible solar energy, the average number of sunny hours per day in each location has been extracted from the solar Atlas of Colombia [61].

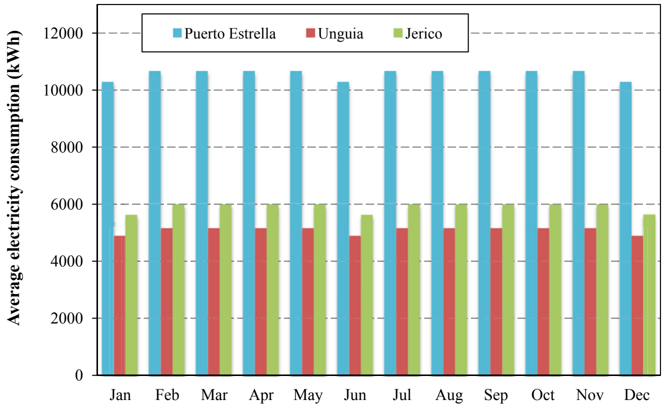


Fig. 3. Average electricity consumption for each location.

2.4. *Major components*

Considering the available products on the Colombian market, a list of components has been selected and their prices have been found through different distributers and fabricants. Accordingly, the best choices in terms of operation & maintenance costs, lifetime, base cost and additional expenses have been chosen. The chosen components and their corresponding costs are shown in Table 2.

2.5. *PV panels*

Photovoltaic system is an interconnection PV module producing direct current electricity from solar energy. Solar panels are made of individual solar cells, connected together and usually rated as 12-V solar panels, although higher voltages are also available. A 12-V solar panel produces around 14–18 V when connected to a load and also is capable of charging a 12-V battery. In this study, KYOCERA kdp series of 320 W and 240 W are considered. Both capital and replacement cost for a KYOCERA kdp series of 320 W solar panel system were considered to be $800, while for the KYOCERA kdp series of 240 W solar panel system they were assumed to be $720 [62]. The lifetime of the PV panels is estimated to be 20 years and no tracking system was used.

2.6. *Wind turbine*

In a wind turbine, electricity is generated by converting the kinetic energy of wind into electrical energy. Wind turbine farms are becoming important sources of renewable energy and are used to reduce reliance on fossil fuels and consequently pollutant emissions [63,64]. The wind turbines used in this analysis are Aeolos-H10 and Aeolos-H20 with rated capacities of 10 kW and 20 kW respectively and AC voltage output. The capital cost associated to the wind energy system includes the cost of turbine, tower, inverter, wiring, painting, anti-corrosion packages and the installation cost. It is estimated that the total capital cost of a 10 kW wind turbine is $27,378 while it is $47,817 for a 20 kW one while a hub height of 18 m is considered for both units [58]. The O&M costs appear to be strongly correlated with the turbine age and accordingly in the first few years of operation, the manufacturer's warranty implies a low level of O&M expenses while starting from the 10th year higher levels of repairs and reinvestments should be expected.

2.7. *Diesel generator*

The low reliability of PV-wind hybrid systems is a major barrier for market development of such renewable systems [65]. Therefore, diesel generators have been widely employed along with renewable sources to increase the reliability of such systems. A diesel generator SD010 with a liquid cooled engine and 10 kW of rated

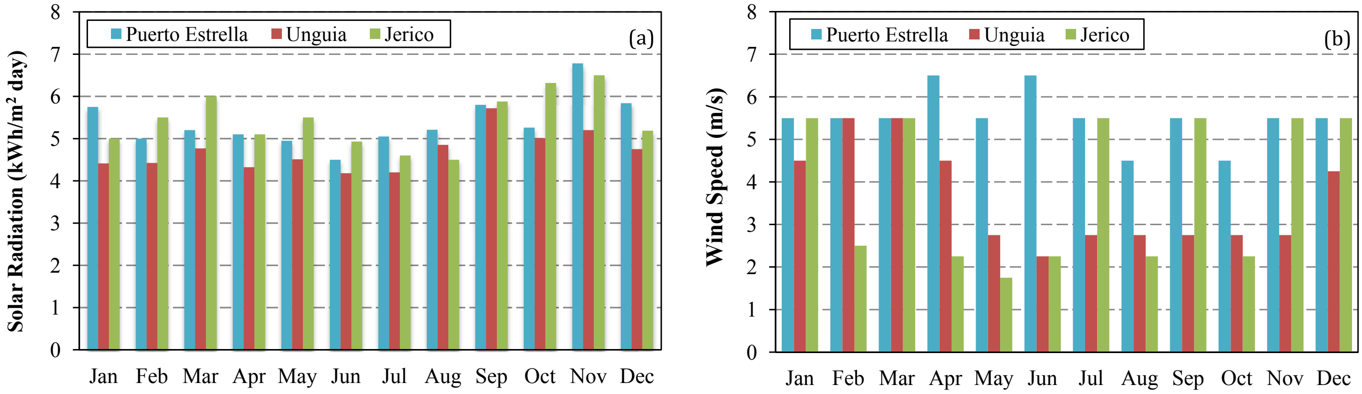


Fig. 4. Average monthly solar radiation and wind velocity for each location.

Table 2
Components characteristics and their corresponding costs [46,47,62–64,67].

Component	Homer suffix	Capital cost	Replacement cost	Operation & maintenance	Fabricant
PV 320 W	PV	$800	$720	$8	KYOCERA
PV 240 W	PV	$750	$ 700	$ 7	KYOCERA
Converter (5 KW)	Converter	$4650	$4185	$120	SOLAREDGE
Batteries (4KS25P) 4 V 1900 Ah	S4KS25P	$1306	$1175	$130/year	SURRETE
Batteries (H3000) 2 V 3000 Ah	H3000	$2171	$1953	$217/year	HOPPECKE
Diesel Generator (10 KW)	Generator	$6000	$5000	$0.075/h	GENERAC
Aeolos-H 10 kW Wind Turbine	AH10	$27,378	$24,640	$273/year	AEOLOS
Aeolos-H 20 kW Wind Turbine	AH20	$47,817	$43,035	$430/year	AEOLOS

power is selected in this study [66]. The initial capital cost of the generator was assumed to be 6000 $/kW, and the replacement and operational costs are 5000 $/kW and 0.075 $/h respectively. its corresponding operating lifetime was also considered to be 85,000 h as liquid-cooled engines last much longer than air-cooled ones [64]. The current diesel price, taken from World Bank data [34], in Colombia is 1.1 $/liter [18].

2.8. Batteries

Due to the intermittent nature of wind and solar energy, a power system based on wind turbine and photovoltaic dictates the necessity of using battery storage facilities in order to ensure a constant power supply [28]. Surrette [67] and Hoppecke [39] batteries were chosen as the HOMER equivalent batteries in the present work. The capital cost for Surrette 4ks25p and Hoppecke 24 are considered to be $1306 and $2171 respectively while the replacement costs are assumed to be $1175 and $1953 respectively.

2.9. Inverter

The inverter is one of the key components of the system as it converts the DC electricity produced by the PV modules into AC electricity (wind turbines are not considered since they already have the inverter included in the capital cost and the diesel generator produces AC voltage). SolarEdge SE5000 US PV Inverter 5 kW [38], with the efficiency of 94%, installation and replacement costs of $4185, and lifetime of 12.5 years, is considered for this analysis.

2.10. Scenarios

HOMER software has been employed to carry out the economic optimization of different configurations for each community. The ultimate purpose of this analysis is to assess the technical and economic viability of seven different configurations, including all possible combinations of PV cells, wind turbines, diesel generators, and batteries and to determine the best configuration for electrical power production in each location. As is also illustrated in Fig. 5, the simulation was conducted for the following configurations:

- Diesel generator (Case1)
- Photovoltaic (Case2)
- Wind turbine (Case 3)
- Solar-Wind hybrid (Case 4)
- Solar-Diesel hybrid (Case 5)
- Wind-Diesel hybrid (Case 6)
- Solar-Wind-Diesel hybrid (Case 7)

In remote locations, where no electric grid is available, the first short-term solution can be the diesel generator. However, these systems may suffer from high cost of maintenance, fuel supply and considerable amount of pollutants emission. In the second case (photovoltaic), solar panels provide the energy that is fed to the controller, which charges the batteries and also supplies power to the low voltage devices (in DC). The AC inverter is fed directly by the battery and provides high voltage power (in AC) to the required devices [64]. In the third case (wind turbine), wind turbines provide the AC energy, which is converted to DC in order to be used by the batteries, which are in turn used later to supply power to the low voltage devices (in DC). The battery introduces power to the AC inverter which then is going to be utilized in appliances with high voltage demand.

The main advantage of hybrid systems is supplying energy from different sources. Considering the fact that one source may not be sufficient to fulfill the entire load at several periods throughout a year. As the first hybrid configuration (Case 4), photovoltaic and wind turbine systems were used in a hybrid system along with battery banks. The battery bank stores energy when excess wind and solar energy is available and gives it back when it is demanded. In cases 5 and 6, the hybrid system is composed of photovoltaic/diesel generator and wind turbine/diesel generator respectively. Although, the diesel generator is able to supply endless energy (with the fuel constraint), the economic aspect is the main constraint for these cases which prevents the system to solely depends on diesel generators. Finally, Case 7 is composed of PV, wind, diesel generator and battery storage to ensure a reliable and constant power supply while also considering the economic aspects of the system.

3. Methodology

As was previously mentioned, photovoltaic panels, wind turbines and diesel generators are the units that are taken into consideration for power generation. In this regard, the total generated energy (E_T) is defined as the sum of generated energy by photovoltaic (E_{PV}), wind energy (E_W), and diesel generator (E_{DG}). Accordingly, the share of each energy sources in the total produced energy can be expressed as follows:

$$f_{PV} = \frac{E_{PV}}{E_T} \tag{1}$$

$$f_{WG} = \frac{E_W}{E_T} \tag{2}$$

$$f_{DG} = \frac{E_{DG}}{E_T} \tag{3}$$

The three principal economic indicators considered in the present analysis are the total net present cost (NPC), the levelized cost of energy (COE), and the initial capital cost. NPC is more reliable compared to COE as an economic parameter since the value of COE is arbitrary to some extent while NPC stems from a mathematical concept [8]. The initial capital cost (C_{cap}) of a component is the total installed cost of that component at the beginning of the project. The annualized capital cost of each component is [68,69]:

$$C_{acap} = C_{cap}{}^{*}CRF \tag{4}$$

where CRF is the capital recovery factor, given by Ref. [70]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5}$$

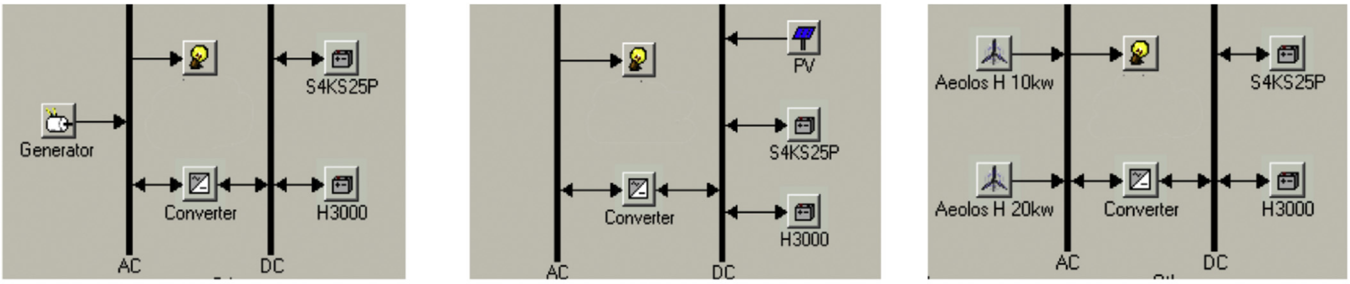
where N and i are the system lifetime, and the annual real interest rate.

Furthermore, the salvage value, operating cost and renewable fraction (RF) have been also evaluated and reported to provide much insight into the operation of optimal cases in different areas.

The total net present cost of each configuration can be calculated as follows [19]:

$$NPC\ (\$) = \frac{TAC}{CRF} \tag{6}$$

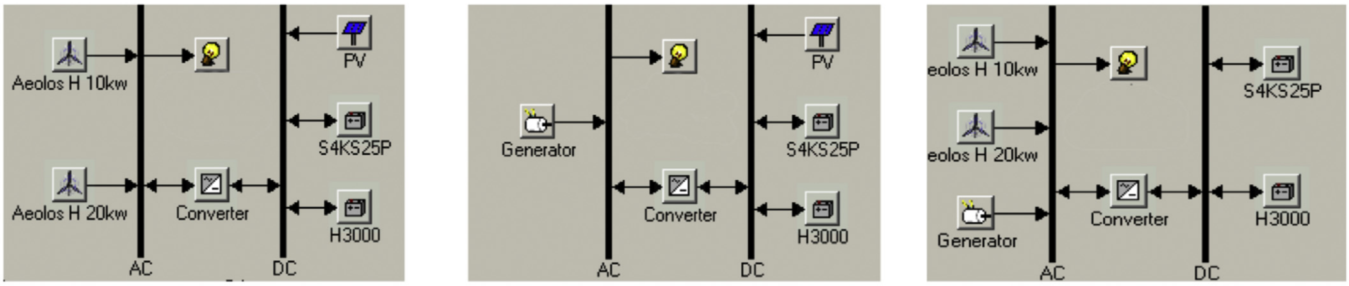
where TAC is the total annualized cost (sum of all annualized costs of each system component) that is:



Case 1 Diesel system (off-grid configuration)

Case 2 Solar system (off-grid configuration)

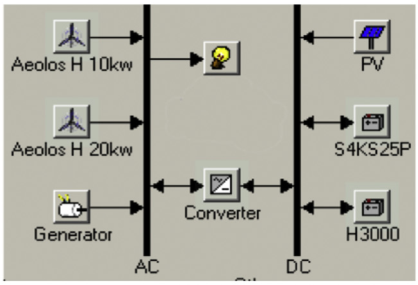
Case 3 Wind system (off-grid configuration)



Case 4 Solar Wind Hybrid system (off-grid configuration)

Case 5 Solar Diesel Hybrid system (off-grid configuration)

Case 6 Wind Diesel Hybrid system (off-grid configuration)



Case 7 Solar Wind Diesel Hybrid system (off-grid configuration)

Fig. 5. Different off-grid configurations analyzed in HOMER.

$$TAC = C_{acap} + \sum_{i=1}^{n} C_{OM,j} + C_f + \sum_{i=1}^{n} C_{R,i} \tag{7}$$

where n is the number of all the devices in the system, $C_{OM,i}$ is the annual operation and maintenance (O&M) cost for the ith component of the system, C_fC_f is total annual fuel cost and $C_{R,i}$ is the annualized replacement cost for the ith component of the system.

The levelized cost of energy (COE) is defined as the average cost per kWh of useful electrical energy produced by the system. COE is calculated by dividing the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total electric load served. The equation for the COE is as follow:

$$COE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales}} \tag{8}$$

where $C_{ann,tot}$ is the total annualized cost of the system ($/year), and $E_{prim,AC}$, $E_{prim,DC}$, E_{def}, and $E_{grid,sales}$ are the total thermal, AC, DC, deferrable, and grid sales load served energy (kWh/year), respectively.

The salvage value, which represents the remaining value of a component of the power system at the end of the project lifetime, is assumed to undergo a linear depreciation, meaning that it is directly proportional to the remaining life. Moreover, it is based on the replacement cost rather than on the initial capital cost [9] and the value for each component can be expressed as following:

$$S = C_{rep}\frac{R_{rem}}{R_{comp}} \tag{9}$$

where R_{rem}, R_{comp}, and C_{rep} are the remaining cost of the component, component lifetime (year), and the replacement cost ($) respectively.

The total operating cost (TOC) is the sum of the annual operation and maintenance (O&M) costs, total fuel cost, and annualized replacement cost minus the annualized salvage value defined as:

$$TOC = \sum_{i=1}^{n} C_{OM,j} + C_f + \sum_{i=1}^{n} C_{R,i} - \sum_{i=1}^{n} C_{S,i} \tag{10}$$

where n is the number of all the devices in the system, $C_{OM,i}$ is the annual operation and maintenance (O&M) cost for the ith component of the system, C_f is total annual fuel cost, $C_{R,i}$ is the annualized replacement cost for the ith component of the system and $C_{S,i}$ is the salvage value of component i.

Once the optimal configurations for each area are determined, the resulting environmental influence of each system has been also calculated. The total carbon dioxide production has been employed as criteria to evaluate the corresponding environmental effect. Furthermore, for the achieved optimal configurations, the yearly electrical energy generation of each component has also been determined.

4. Results and discussions

The optimal system designs obtained from the simulation of cases 1 to 7 for each considered community are presented in Tables 3–5. As can be seen in these tables, in order to compare the configurations from the environmental standpoints, the resulting yearly CO_2 production for each case has been determined and demonstrated. The overall yearly electrical energy produced by each generation type (PV, wind and diesel generation) is also calculated. It can be noted that several cases are able to meet the required electrical load through 100% renewable energy. Hence, in depth economical analysis is in order to determine the most economically convenient case for each location. As such, four indicators were selected to investigate the proposed configurations from economic view point: namely initial capital of the system (in terms of dollar), Operating cost ($/yr), total NPC ($) and COE ($/kWh).

4.1. *Optimal design for Puerto Estrella*

As shown in Fig. 6, case 7 (solar, wind and diesel) with the lowest NPC value results in the most economic design for Puerto Estrella. The optimal size of the system for case 7 is: 500 PV panels (320 W each), 1 Aeolos 10 kW wind turbine, diesel generator of 25 kW, 250 Surrette batteries s4ks25p, and inverter of 80 kW. This configuration corresponds to an initial capital of $521,078, an operating cost of 24,652 $/year, a total net present cost of $836,210 and a total cost of energy of 0.473 $/kWh. Moreover, as can be seen in Fig. 6, case 3 (wind turbine) leads to the worst system design from economic standpoint due to the high capital cost of wind turbines. Another important point, interpreted from Table 3, is that in Cases 2, 5 and 7, the major portion of the electrical load is supplied by solar energy, while case 2 is the most sustainable configuring among these three cases, achieving 100% renewable energy target. The total CO_2 emissions for Case 5 and 7 are 5548 kg/year and 4262 kg/year, showing that case 5 results in the least sustainable configuration.

Fig. 7a and b demonstrate the electricity supply breakdown for Cases 5 and 7, where the yellow bars represent the power produced by solar panels, while the black and green ones show the power generated by diesel generator and wind turbine. Comparing Figs. 7a and 3 shows that the monthly electricity production closely matches the monthly electricity consumption, while a variation in the average power produced can be seen due to the intermittent nature of renewable energy resources [9]. Similarly, as shown in Fig. 7b, the power generated by the wind turbine is a minor portion of total generated power generated. Hence, it can be concluded that, for the considered load scale in this study, electrical production using PV panels is more economically profitable than employing wind turbines. However, it should be noted that the wind turbines could be economically more competitive at higher production scales [71].

Furthermore, despite the fact that the diesel system is the cheapest choice in the short term, the PV array has been selected as the dominant system configuration in a long-term analysis. Another important consideration is the excess energy produced in case 7 (115,927 kWh/year) which can be used in case of population increment or to expand the economic activities, contributing to the village's development.

It should also be mentioned that, although Homer determined the diesel-battery system as the optimal configuration for Puerto Estrella, the cheapest design in short-run can be achieved by the diesel-based system, having an initial cost of about $54,000, operating cost of 174,541 $/year and net present cost of 2,285,223 (which is the second highest after Case 3), and cost of energy of 1 $/kWh.

Overall, the simulation results suggest that Case 7 results in the best design with the lowest NPC value, meaning a higher capital recovery factor and accordingly the faster recovery of capital and operating costs.

4.2. *Optimal design for Unguia*

The energetic and economic results for Unguia are shown in Table 4 and Fig. 8, respectively. Considering the economic indicators for Unguia, Case 2, 5 and 7 have been selected, leading to the lowest net present value, operating cost, initial cost and the cost of energy compared to the other cases. Similar to Puerto Estrella, the majority of the electrical load is produced by solar panels. Among these three configurations, as shown in Fig. 8, case 5 results in the most economical design in Unguia due to its lowest NPC value, while achieving an acceptable renewable fraction of 98%. Furthermore, as seen in Table 4, Case 2 results in the most sustainable configuration, achieving the renewable fraction of 1, while the CO_2 emissions for Case 5 and 7 are 5120 kg/year and 3169 kg/year respectively. The optimal size of the system for case 5 is: 313 PV panels (each with 320 W capacity), one 25 kW Diesel generator, 100 Surrette s4ks25p batteries, and a 30 kW inverter. This design leads to an initial cost of $227,350, an operational cost of 11,373 $/year, a total net present cost of $372,736 and a total energy cost of 0.444 $/kWh.

Table 3
Optimized results for the proposed configurations in Puerto Estrella.

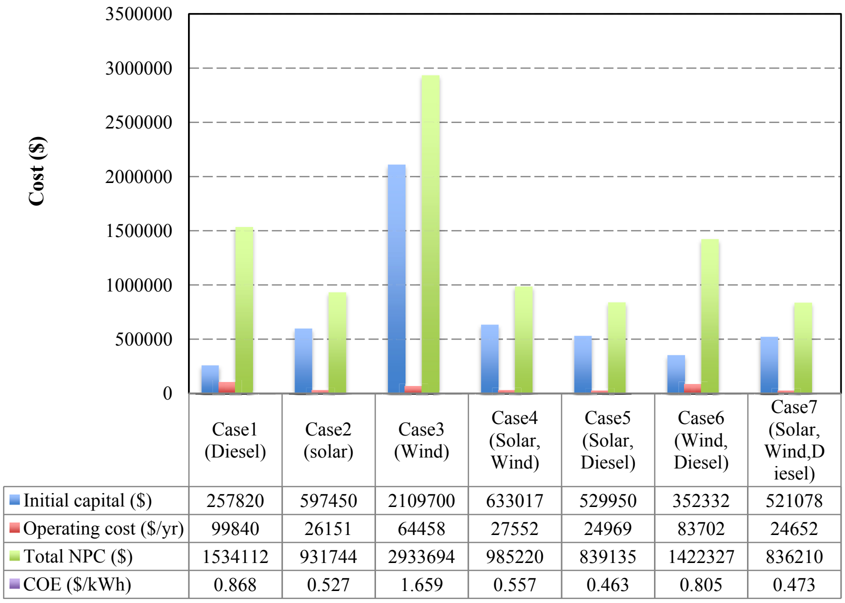
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
PV (kW)	–	350	–	300	170	–	160
Generator (kW)	50	–	–	–	25	25	25
Converter (kW)	80	80	80	100	80	80	80
F_{PV} (%)	0	100	0	97	98	0	96
F_{DG} (%)	100	0	0	0	2	76	1
F_{WG} (%)	0	0	100	3	0	24	3
PV (kWh/yr)	–	642,524	–	550,735	312,084	–	293,726
DG (kWh/yr)	145,285	–	–	–	4941	158,139	3801
Wind (kWh/yr)	–	–	481,775	15,634	–	38,542	9636
CO_2 emissions (kg/yr)	162,142	–	–	–	5548	131,026	4262
Renewable fraction (–)	0.0	1.0	1.0	1.0	0.98	0.24	0.99
Annual operational hours of generator (h)	4323	–	–	–	326	4799	245

Table 4
Optimized results for the proposed configurations in Unguia.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
PV (kW)	–	200	–	200	100	–	100
Generator (kW)	10	–	–	–	25	10	10
Converter (kW)	30	40	40	40	30	30	30
F_{PV} (%)	0	100	0	99	98	0	97
F_{DG} (%)	100	0	0	0	2	96	1
F_{WG} (%)	0	0	100	1	0	4	2
PV (kWh/yr)	–	360,591	–	360,951	180,475	–	180,475
DG (kWh/yr)	78,303	–	–	–	4553	74,906	2789
Wind (kWh/yr)	–	–	448,190	2988	–	2988	2988
CO_2 emissions (kg/yr)	85,781	–	–	–	5120	82,060	3169
Renewable fraction (–)	0.0	1.0	1.0	1.0	0.98	0.0	0.99
Annual operational hours of generator (h)	7831	–	–	–	308	7492	550

Table 5
Optimized results for the proposed configurations in Jerico.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
PV (kW)	–	200	–	200	150	–	150
Generator (kW)	25	–	–	–	25	25	25
Converter (kW)	40	40	40	40	40	40	40
F_{PV} (%)	0	100	0	99	98	0	97
F_{DG} (%)	100	0	0	0	2	96	2
F_{WG} (%)	0	0	100	1	0	4	1
PV (kWh/yr)	–	356,460	–	356,460	267,345	–	267,345
DG (kWh/yr)	84,584	–	–	–	5250	80,281	4465
Wind (kWh/yr)	–	–	481,770	3392	–	3392	3392
CO_2 emissions (kg/yr)	93,543	–	–	–	5923	88,943	5052
Renewable fraction (–)	0.000	1.000	1	1.000	0.980	0.040	0.980
Annual operational hours of generator (h)	4223	–	–	–	373	4158	331
Capacity shortage fraction (–)	–	–	0.5	–	–	–	–



	Case1 (Diesel)	Case2 (solar)	Case3 (Wind)	Case4 (Solar, Wind)	Case5 (Solar, Diesel)	Case6 (Wind, Diesel)	Case7 (Solar, Wind,Diesel)
🟦 Initial capital ($)	257820	597450	2109700	633017	529950	352332	521078
🟥 Operating cost ($/yr)	99840	26151	64458	27552	24969	83702	24652
🟩 Total NPC ($)	1534112	931744	2933694	985220	839135	1422327	836210
🟪 COE ($/kWh)	0.868	0.527	1.659	0.557	0.463	0.805	0.473

Fig. 6. System costs associated with each case investigated for Puerto Estrella.

It should be noted that the wind speed in Unguia is too low to make wind turbines profitable in this region. In addition, although the diesel system is the most cost-effective design in a short-term, solar PVs are still preferable due to their higher share of power supply ($F_{PV} = 0.98$ as opposed to $F_{DG} = 0.02$).

Although both Case 5 and 7 have an annual excess of energy, Case 5 gives a higher excess of 93,840 kWh/year which could not only be used in case of population increase, heating systems or extra economical activities, but also as a future possibility of selling in case the village's electric system would be connected to the grid. Finally, due to having the lowest cost compared to other configurations, Case 5 is selected as the most economical design for Unguia.

4.3. Optimal design for Jerico

The obtained energetic and economic results for Jerico are

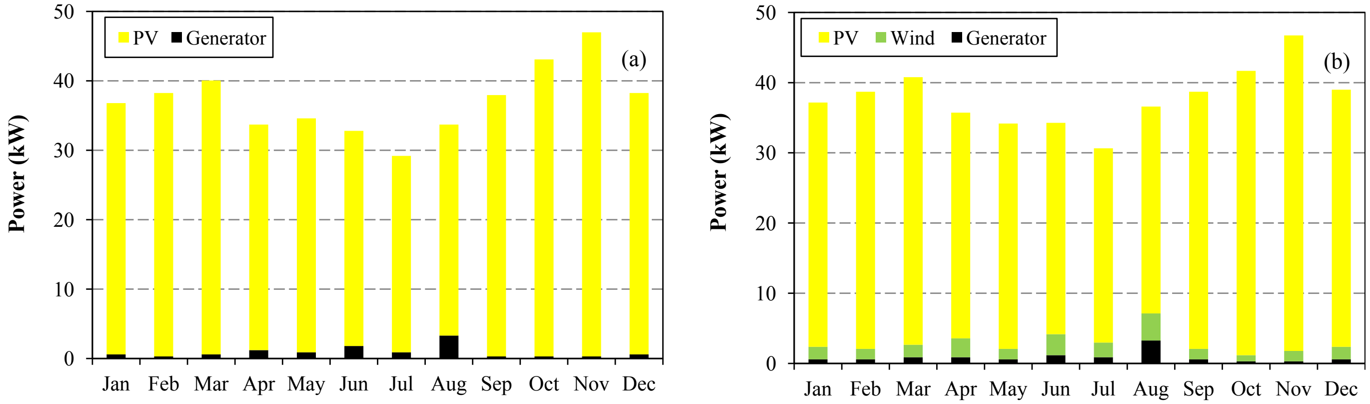
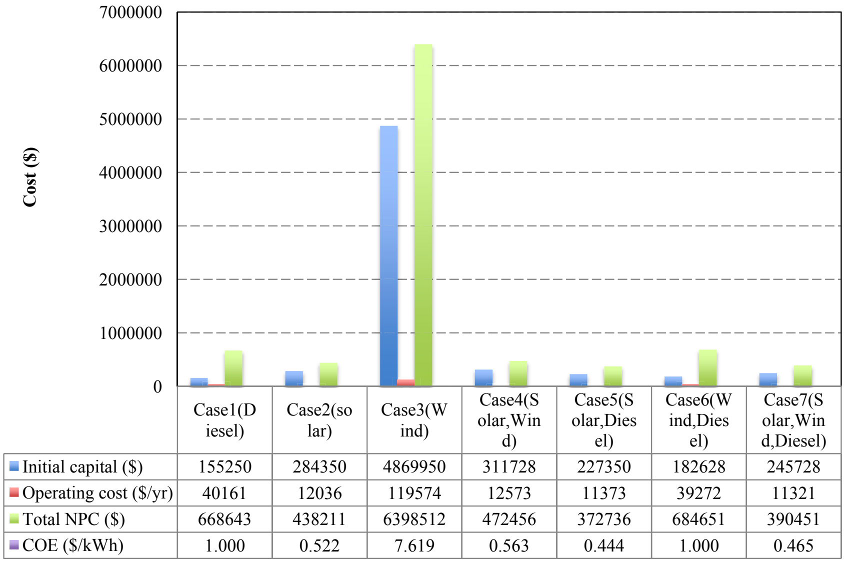


Fig. 7. Total electricity production in Case 5 and Case 7 for Puerto Estrella.



	Case1(Diesel)	Case2(solar)	Case3(Wind)	Case4(Solar,Wind)	Case5(Solar,Diesel)	Case6(Wind,Diesel)	Case7(Solar,Wind,Diesel)
🟦 Initial capital ($)	155250	284350	4869950	311728	227350	182628	245728
🟥 Operating cost ($/yr)	40161	12036	119574	12573	11373	39272	11321
🟩 Total NPC ($)	668643	438211	6398512	472456	372736	684651	390451
🟪 COE ($/kWh)	1.000	0.522	7.619	0.563	0.444	1.000	0.465

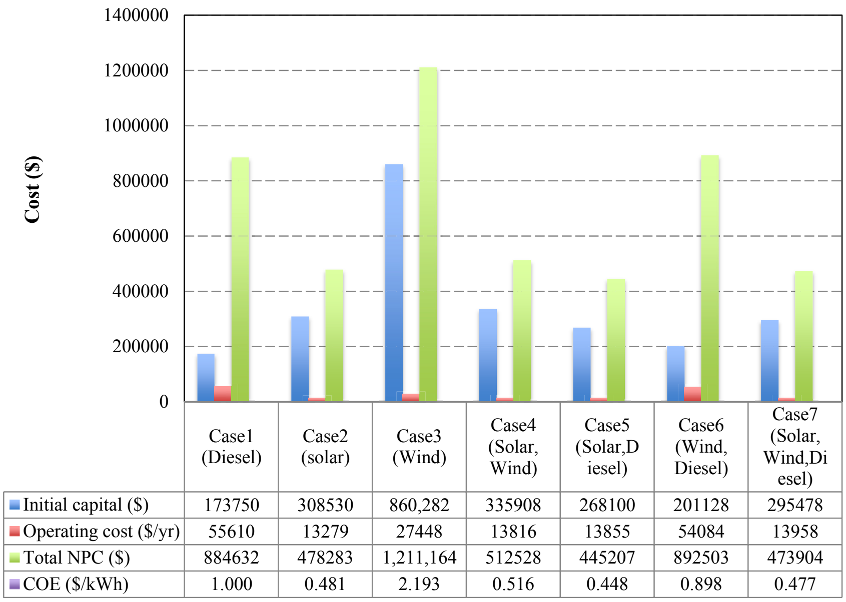
Fig. 8. System costs associated with each case investigated for Unguia.

shown in Table 5 and Fig. 9, respectively. Since no optimization result was obtained in Case 3 (wind turbine system), the maximum annual capacity shortage constraint was used to obtain simulation results. This term is defined as the maximum allowable value of the capacity shortage fraction, which is the total capacity shortage divided by the total annual electric load. Assuming a fraction of one over two, a result was obtained for the simulation of Case 3, but similar to the previously analyzed locations, it leads to the worst design in the study. Furthermore, Case 3 contributes to the highest net present cost and cost of energy compared to other cases in Jerico. According to Table 5, Cases 2, 4, 5 and 7 are the most sustainable designs, while as shown in Fig. 9, Case 5 (solar-diesel hybrid system) has the lowest investment and net present cost compared to the other cases, meeting the environmental and economic objectives simultaneously. The optimal size of the system for case 5 is: 469 solar panels (each 320 W capacity), one 25 kW Diesel generator, 100 Surrette s4ks25p batteries and a 40 kW Inverter. This configuration leads to an initial cost of $268,100, an operating cost of 13,855 $/year, a total Net Present Cost of $445,207 and the total cost of energy of 0.448 $/kWh.

4.4. Cost of components for each optimal case

In this section, the cost breakdown of optimal designs discussed in Sections 4.1, 4.2, and 4.3 is presented in detail. As discussed earlier, the total cost of each design mainly includes the capital costs, the replacement and operating costs, and the fuel cost. Fig. 10a illustrates the share of each cost component for Case 7 which was selected as the optimal design for Puerto Estrella. As expected, the highest cost is attributed to the system capital cost, followed by the replacement and operating costs. According to Fig. 10a, the most expensive component of the system is the battery, representing about 58% of the system capital and replacement costs and 37% of the system total cost. Furthermore, wind turbine represents the lowest portion of the system capital and replacement costs, while the operating cost associated with wind turbine is almost zero.

Moreover, the cost breakdown for Case 5, the final optimal design for Unguia, is presented in Fig. 10b. As shown in this figure, the largest cost component is the capital cost, while the replacement and operating costs are the second and third most expensive parts of the system's total cost. It is also observed that the batteries contribute to about 53% of the system capital cost and 70% of the



	Case1 (Diesel)	Case2 (solar)	Case3 (Wind)	Case4 (Solar, Wind)	Case5 (Solar,Diesel)	Case6 (Wind, Diesel)	Case7 (Solar, Wind,Diesel)
Initial capital ($)	173750	308530	860,282	335908	268100	201128	295478
Operating cost ($/yr)	55610	13279	27448	13816	13855	54084	13958
Total NPC ($)	884632	478283	1,211,164	512528	445207	892503	473904
COE ($/kWh)	1.000	0.481	2.193	0.516	0.448	0.898	0.477

Fig. 9. System costs associated with each case investigated for Jerico.

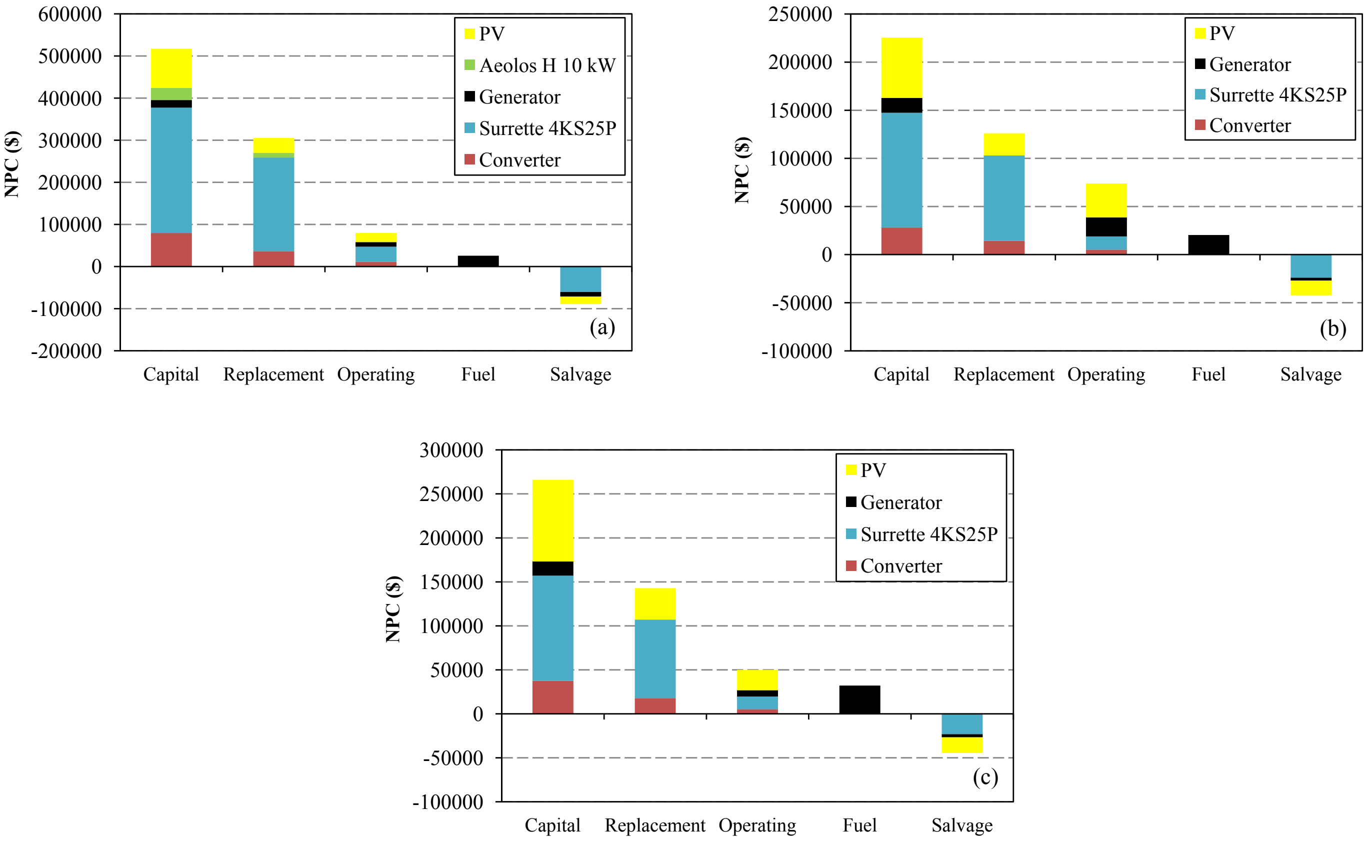


Fig. 10. Cost breakdowns of (a) Case 7 in Puerto Estrella, (b) Case 5 in Unguia and (c) Case 5 in Jerico.

replacement costs, which is about 33% of the total cost of the system.

Fig. 10c shows the summary of the cost of components for Case 5 which was chosen as the best enviro-economic design for Jerico. According to this figure, batteries results in the highest portion of capital, replacement and operating costs, while solar panels are the second most expensive parts of the system, comprising about 30% of the total cost of the system. The results presented in Fig. 10c also indicate that 32% of the total cost of the system is due to replacement cost.

Finally, Tables 6 and 7 list the size of optimal designs for each location and the corresponding cost-related results respectively.

Table 6

The nominal capacity of main system components of the optimal hybrid plant obtained from techno-economic analysis.

Location	Optimal configuration	PV (kW)	Wind turbine (kW)	Generator (kW)	Number of battery (–)	Converter (kW)
Puerto Estrella	Case 7	160	10	25	250	80
Unguia	Case 5	100	–	25	100	30
Jerico	Case 5	150	–	25	100	40

Table 7

The results of economic analysis for the optimal hybrid plant at the locations considered in this study.

Location	Optimal configuration	Initial capital ($)	Operating cost ($/yr)	Total NPC ($)	COE ($/kWh)	Renewable fraction (–)	Diesel (liter)	Generator (h)
Puerto Estrella	Case 7	521,078	24,652	836,210	0.473	0.99	1618	245
Unguia	Case 5	227,350	11,373	372,736	0.444	0.98	1944	308
Jerico	Case 5	268,100	13,855	445,207	0.448	0.98	2249	373

5. Conclusions

This paper presented a systematic evaluation of different off-grid configurations in three small rural communities in Colombia. Seven design cases were proposed and assessed based on combinations of diesel generator, solar panels and wind turbine units. A dynamic model of the plant was developed in HOMER software to perform a complete parametric analysis on the system configurations and to select the most convenient one from the economic perspectives. The net present cost (NPC), initial capital cost, and cost of energy (COE) were selected as the economic indicators. The resulting yearly CO_2 emissions, as the environmental index, were also determined. The results showed that the combined diesel-renewable configurations have a very low carbon footprint; in Puerto Estrella as an instance, the hybrid configuration results in an emission of 4262 kg CO_2/year, which is about 2.6% of the resulting emission of the diesel-based system (162,142 kg CO_2/year). The ratio between the CO_2 emissions of diesel-hybrid and diesel only systems is 3.6% in Unguia and 5.4% in Jerico. The cost analysis results revealed that the combination of diesel, solar PVs, and wind turbines, with an initial capital investment of $521,078 and a NPV of $836,210, was the optimal option in Puerto Estrella, using which a renewable fraction of 99% can be obtained while covering the load demand required and even providing addition electrical energy. In Unguia and Jerico, solar-diesel system led to the most economically convenient design, taking into account the load requirements of these communities and the available renewable resources in their corresponding regions.

In case the capital cost would be considered as the only criteria, among the proposed configurations, the diesel-based system is the most convenient one. In Puerto Estrella the required initial investment for the diesel-based system is nearly 50% less than the needed investment of the hybrid configuration. Nevertheless, a part from the significantly higher CO_2 emissions, a notable obstacle which impedes the application of this unit is the difficulty of transporting fuel to these rural areas.

Although the entirely renewable and hybrid configurations are apparently the most preferred designs from the environmental viewpoint and they might also be economically convenient on the long run, requiring significantly higher investment cost is the major barrier which hinders the possibility of application of these systems in the considered communities. In addition, apart from the required initial investment, application of these units results in operation and maintenance costs which clearly cannot be afforded by the considered low-income communities.

The Colombian government can play a significant role in facilitating the application of the hybrid renewable based configurations for electrification in these rural areas. Nevertheless, even the recent legislation for supporting the application of these units only includes tax reductions and exemptions; which is not a sufficient support for providing the low-income communities with the possibility of employing these systems. In case adequate incentives and supporting policies would be provided by the government, the configurations and the optimal size of the components which were proposed in this study can be effectively employed to provide electricity for these communities in the most economically convenient way.

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