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Techno-Economic Assessment of Renewable Energy-based Microgrids in the Amazon Remote Communities in Ecuador

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Several remote communities have limited electricity access and are mainly dependent on environmentally damaging fossil fuels. The installation of microgrid networks and green energy initiatives are currently addressing this issue. Thus, this paper proposes the techno-economic assessment of a microgrid that comprises Photovoltaic (PV) arrays, a micro hydro turbine, and diesel generation. Two scenarios are evaluated considering the inclusion or not of diesel generation. This model is performed in HOMER. The results demonstrate that the best option in economics is to invest in a PV/Hydro/Diesel microgrid, resulting in an Net Present Cost (NPC) of 2.33M$, and a Cost of Energy ($COE$) of 0.194$/kWh. Furthermore, to address diesel price uncertainties, a sensitivity analysis was carried out based on three different projected diesel prices.

Nomenclature

Index

e	Generation or Storage index
t	Time interval

Parameters

α_e	Emission factor for CO_2 emissions for a generation/storage e [Ton/kWh]
α_{PV}	Temperature coefficient of power [$\%/^{\circ}C$]
ΔT	Duration between each time interval [h]
$\dot{Q}_t$	Hydro turbine flow rate [m^3/s]
η_{BC}	Battery efficiency for charging [%]
η_{BD}	Battery efficiency for discharging [%]
η_{hyd}	Hydro turbine efficiency [%]
ρ_w	Water density [kg/m^3]
σ	Battery self-discharge rate

ξ	Conversion coefficient
Bat	Battery capacity [kWh]
CRF	Capital Recovery Factor
CT	Annualized net present total cost for the planning horizon [\$/yr]
D	Number of years for planing horizon
ET	Total electrical energy served [kWh/yr]
ET_g	Total electrical energy served by source g [kWh/yr]
G_{AC}	Solar radiation incident on the PV array in the current time step $[W/m^2]$
G_{STC}	Incident PV radiation at standard test conditions $[W/m^2]$
H_{hyd}	Effective head [m]
P_{STC}	Maximum test power under standard test conditions $[W/m^2]$
r	Discount rate [%])
T_c	PV cell temperature $[°C]$
$T_{c,STC}$	PV cell temperature under standard test conditions $[25\ °C]$

Sets

$\mathcal{E}$	Set of generation and storage

Variables

CO_2	Carbon dioxyde emissions [Ton/yr]
COE	Levelized Cost of Energy [\$/kWh]
E_e	Energy produced by source e [kWh]
NPC	Net Present Cost [\$]
P_H	Power output of hydro turbine [kW]
P_{def}	Deficit power [kW]
P_{PV}	Power Output of PV Array [kW]
$P_{RE,exc}$	Surplus power from RE [kW]
SOC	State of charge of the battery [kWh]

1 Introduction

For the development of the communities [1] the electricity access is considered as vital. But several people worldwide, especially from developing countries, still do not have access to electricity. Bringing electricity to rural areas or remote communities is a challenge for a long time since it involves costly technical investments and maintenance [2, 3]. Rural areas are quite common for the disappearance of the distribution grid. Consequently, the microgrid must be able to work independently without interference while the grid is out of service [4].

During 2007-2017, Ecuador had substantial government investment in the energy sector, especially in RE, such as its 1,500 MW hydropower plant Coca Codo Sinclar. In addition, electricity coverage increased significantly reaching a coverage superior to 97% [5]. Although the Amazon is one of the regions with lowest electricity load demand (around 2 %), it is still the lowest coverage zone (93.7 %). In the Amazon region, various hydropower plants were built, increasing the national electricity coverage, but there is no coverage in many rural areas since investments in new electrical equipment are very costly, such as distribution and transmission lines, considering its low electricity demand [6]. Furthermore, because these rural areas are far from main generators, there are significant power losses [7].

The Amazon forest is known as the lung of the planet [8], however, it experiences various environmental problems such as fuel leaks that occurred recently [9]. Furthermore, in various rural areas, the electricity is generated by small and polluting power plants, aggravating the environmental concerns. Some renewable energy (RE) initiatives have been initiated to resolve these concerns. The Eurosolar initiative, for instance, encouraged the [10] installation of panels. These adjustments are not yet enough to fix the environmental and energy coverage.

The construction of transmission and distribution lines is expensive for electricity companies, hindering electricity access to remote rural communities. For example, according to [11], the construction cost of three-phase transmission line of 230kV is 959700 $/mile. Moreover, if the transmission or distribution lines are longer, the Joule effect losses and voltage drops will increase. This will reduce the reliability and quality of the system [12].

A proper solution is to invest in isolated microgrids, which are clusters of loads, distributed generation units, and energy storage systems operated in coordination to reliably supply electricity [13]. Hence, many studies have proposed novel methodologies for the operation and management of microgrids. The authors of [14] proposed a practical energy management system of microgrids considering the connection or not with a main grid. The authors of [15] studied the integration and decentralized control of solar home systems for off-grid community applications.

Distributed energy generation (DER) from renewable energy (RE) is used to address the polluting problems of fossil fuel generation [16, 12]. Thus, some other authors proposed the inclusion of RE in the planning problem of microgrids. In [17], the inclusion of RE in remote communities' microgrids in Canada was studied. In [18], a bi-level program is presented for the microgrid planning problem considering compressed air energy storage. The authors of [19] studied the enhancement of microgrid planning performance based on direct load control.

These studies and others presented many mathematical methods, but HOMER Pro remains a robust microgrid planning software that is used universally [20]. Hence, the authors of [21] used HOMER to integrate the development of a hybrid microgrid for microfinance institutions in rural areas of West Africa. In [22], the techno-economic feasibility and size optimisation of a solar PV-battery system for irrigation in isolated regions in Egypt was studied using HOMER. The authors of [23] presented the techno-economic feasibility of an autonomous hybrid renewable energy system in the East District of Sikkim, India, to provide electricity for an academic township. In [24], the power generation planning of a solar-wind microgrid with electric vehicle charging station loads was proposed using HOMER. In [25], the techno-economic assessment of hybrid renewable energy system in Korkadu, India was studied. The authors of [26] used HOMER for quantifying the demand-side management system of a renewable energy system in Chaghi, Pakistan. In [27], various generation-storage configurations were evaluated to reduce CO2 emissions. The authors of [28] studied a grid-independent PV system hybridization with fuel cell-battery/supercapac by using HOMER. In [29], the planning optimization of PV-Diesel-Hydrogen fuel system was performed using HOMER.

The use of hydro generation in the microgrid planning problem was not widely studied so far. In [30] feasibility of hybrid renewable power systems for remote applications in Southern Cameroons was studied considering hydropower. The authors of [31] presented the modeling and optimization of a hybrid microgrid, considering hydro; however, the hydro was considered for storage. In [32], micro-hydro systems in Iran microgrids were proposed.

The objective of this work is to analyze the long-term planning for microgrids in Ecuadorian remote communities to evaluate new electrical solutions. This paper is an extension of an earlier conference [33], which has been significantly refined. In particulate, real-data was used, and the accuracy of the model was improved.
The innovative contributions of this paper are highlighted as follows:

- A formal planning methodology is performed considering real data and micro hydro generation.
- Optimal investment in RE is determined taking into account environmental impact and fuel cost uncertainties in various scenarios

Section 2 describes microgrid planning's problem statement. Section 3 presents the approach and methodology. The case study and the data settings are presented in Section 4. In Section 5 the results are discussed. Finally, Section 6 is devoted to conclusions.

2 Problem Statement

This research aims to evaluate potential electrification alternatives of rural areas in the Amazon in Ecuador. The optimal planning for microgrids is conducted by HOMER Software and considering various real datasets. HOMER has a robust algorithm, which substantially optimizes the planning process to determine the cheapest alternatives for micro-grid or other distributed electric power generation systems [20].

2.1 Microgrid Planning Problem

Various targets and constraints must be studied for the microgrid planning problem. Depending on the time, planning studies are classified into the type of studies. Typically, when the planning horizon is smaller than one year, the study corresponds to the operational planning, whose goal is to control and manage the resources successfully. On the other hand, when the time horizon is various years, the study corresponds to long-term planning, where new or updating electrical equipment needs to be determined to support the loads in the future [34]. Since a grid connection is not possible, the planning studies of a microgrid are limited to the siting and sizing of distributed generation and storage. This works focuses on the power generation and energy storage mix selection and sizing. To this end, the microgrid configurations are implemented in HOMER Energy Pro 3.11 [20].

2.2 Long-Term Planning Objective

The typical objective for long-term planning is minimizing the net present cost (NPC):

$$NPC = \frac{CT}{CRF} \tag{1}$$

where CT is the total annualized costs [\$/yr], and CRF is the capital recovery factor, defined:

$$CRF = \frac{r(1+r)^D}{(1+r)^D - 1} \tag{2}$$

where r is the discount rate [%], and D is the years' number of the planning horizon.
The levelized cost of energy is defined:

$$COE = \frac{CT}{ET} \tag{3}$$

where ET is the yearly electricity supplied [kWh/yr]. This variable is useful to study cost/benefit analysis.

3 Approach and Methodology

3.1 Planning Methodology

In this study, a planning methodology is proposed to identify possible new possibilities for the electrification of rural areas in Ecuador's Amazon region. The following steps are proposed:

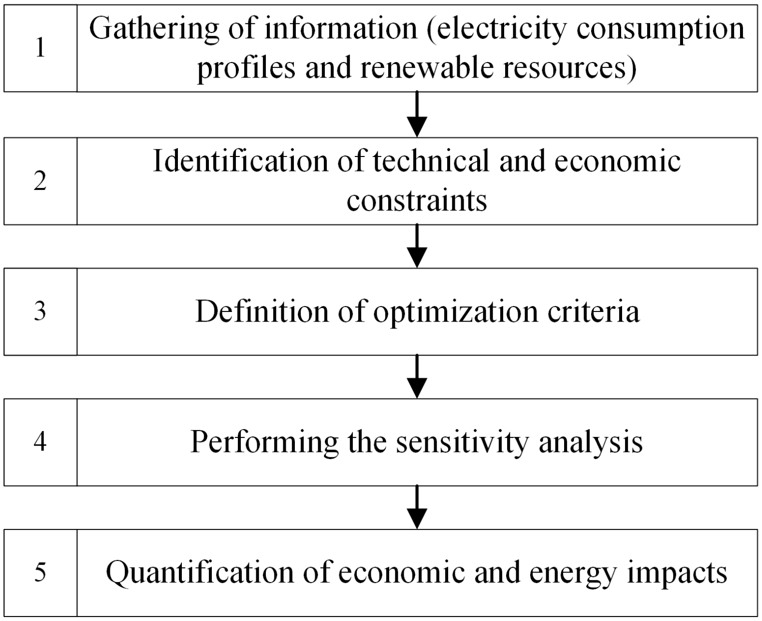

Figure 1: Proposed planning methodology.

The first task was to collect and compile all information from various sources for the residential load and generation input. Then, technical and economic constraints were identified for the correct operation of the microgrid.

HOMER Energy Pro includes its own proprietary robust optimization algorithm for identifying least-cost options, simulating different cases for an entire year, and determining different outputs, such as NPC, COE, and CO_2 emissions, among others. For each of the two selected microgrid configurations, HOMER provides various cases with the corresponding sizing of the distributed generation and storage. For the optimization, it was considered to minimize the NPC. Thus, the case with the minimal NPC is selected. The main objective function of this work is to minimize the net present cost NPC, which is the main criteria selected by investors, such as the Government of Ecuador, for implementing this type of grid system. Therefore, the emissions are used in the paper for evaluation purposes.

After obtaining the optimal results, a sensitivity analysis is performed to address uncertainties. Finally, economic and energy impacts are quantified. The method used for this microgrid planning is depicted in Figure 1.

Two microgrid configurations were selected as a PV/Hydro/Diesel and a PV/Hydro. Note that in [33], a wind turbine was also considered; however, it resulted in all the studied cases in higher NPC values, so for this study, it was not more considered.

3.2 Modeling of system components

The PV power output is calculated:

$$P_{PV} = P_{STC} \cdot \frac{G_{AC}}{G_{STC}} \cdot [1 + \alpha_{PV}(T_c - T_{c,STC})] \tag{4}$$

The electric power output of the micro hydro turbine is obtained:

$$P_H = \frac{\eta_{hyd} \cdot \rho_w \cdot g \cdot H_{hyd}.\dot{Q}_t}{\xi} \tag{5}$$

During low power demand, the battery stores surplus energy and discharges its stored energy at high demand or when the electricity from RE generators is insufficient.
The charging model for the battery storage is given by:

$$SOC(t+1) = SOC(t) \cdot (1-\sigma) + \frac{P_{RE,exc} \cdot \Delta T.\eta_{BC}}{Bat} \tag{6}$$

The discharging model for the battery storage is given by:

$$SOC(t+1) = SOC(t) \cdot (1-\sigma) - \frac{P_{def} \cdot \Delta T.\eta_{BD}}{Bat} \tag{7}$$

3.3 Emissions estimation

The most polluting source is diesel generation. However, even if PV, micro hydro, and battery storage are considered green sources since they do not pollute locally, they have a carbon footprint due to the production, installation, and transportation of the various components.
The CO_2 emissions are also calculated in this work. They are based on the emissions from each generation and storage source.

$$CO_2 = \sum_{g \in \mathcal{E}} \alpha_e \cdot ET_e \tag{8}$$

Various works present their own methodologies to estimate the CO_2 footprint [35, 36, 37, 38]. In general, CO_2 emissions of diesel are calculated based on the fuel consumed, CO_2 emissions of PV, micro hydro, and battery storage are calculated based on the energy consumed.

4 Case Study: Data settings

To perform the microgrid planning, a referential point was selected for the case study. The location corresponds to rural isolated areas in the Amazon region of Ecuador. In Figure 2, the map of the selected location is depicted.

Figure 2: Location of the selected zone [20].

4.1 Residential load

An isolated community of the Ecuadorian Amazon region was selected to perform this planning study. The Shuar area is called Macuma, and it belongs to the Taisha canton in the Morona Santiago province, Ecuador. Macuma has around 3,000 inhabitants, where people are involved in farming, fishing, hunting, logging, and in recent years in tourism.

For this study, the electricity demand data of all Taisha was considered. Taisha is connected to the grid, and it has a population of 18,000 inhabitants. The hourly consumption data were scaled by adjusting the energy demand in the isolated area.

The electricity load profile is depicted in Figure 3, showing a typical residential consumption in a rural area. The energy demand has a little increase in the early morning, then it remains constant, and in the evening it has a considerable increment until midnight.

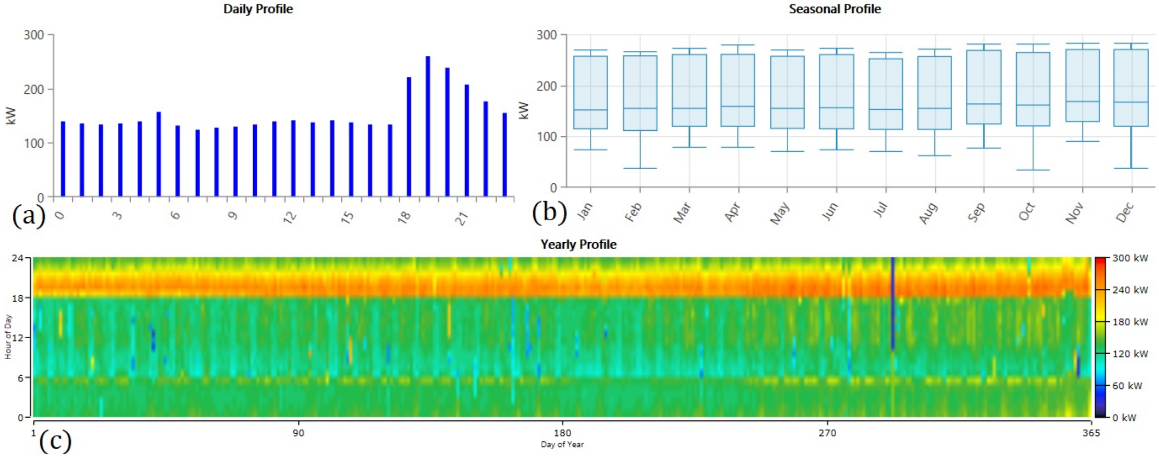

Figure 3: Electrical Load Profiles of the Case Study: (a) 24-h Profile; (b) Yearly Box and Whisker Plot for each month; (c) Yearly Profile [20].

4.2 PV and Battery

HOMER's solar database was used to obtain the hourly solar generation pattern. This data was based on the information from NASA's data. The case study location is in the Morona Santiago Province in Ecuador (2º20'S and 77º27'W). This solar data is accurate enough for the study. In Figure 4, the monthly average solar profile is depicted; observe that the average monthly solar radiation is low in June and July. On the other hand, it is high in October and November. Various local quotes of PV installation and transportation were studied to assume an investment cost of 1,300$/kW and a maintenance cost of 38.64 $/kW/yr in the model. Since new installation studies are not required, replacement costs were assumed to be only 80% of the investment costs, resulting in 1,040 $/kW. Similarly, the investment cost for the battery are assumed to be 300 $/kWh and a maintenance cost of 10 $/kWh/yr. To avoid reliability issues, a minimum battery capacity of 500 kWh is assumed for the optimal search space. For the CO_2 emissions estimation, an emission factor α_{PV} of 63 g/kWh was assumed based on [35]. This value was considered since it represents a high emission factor for ground-mounted PVs compared to diesel emissions. An emission factor α_{Bat} of 52 g/kWh of CO_2 was assumed for the battery, based on [39], since lead-acid batteries were selected for this study.

Figure 4: Average monthly radiation and clearness index [20].

4.3 Micro Hydro

The Macuma River flow data log was taken 50km upstream in an area of easier access. The local municipality provided the data. The information is considered valid since it corresponds to the same river and the affluent downstream is of insignificant flow. According to the data, the hydroelectric volume flow has an average of 1,500 L/s and is fluctuating each month of the year. An investment cost of 2,260 \$/kW was considered based on [40]. The most optimal model resulted in the Generic micro Hydro 100 kW, and thus a total initial investment cost of \$226,000. Similarly, 80% of this value was considered for replacement, resulting in \$180,800. The total operation and maintenance costs are 13,795\$/yr.
Figure 5 illustrates the Monthly Average Hydro Stream Flow. Note that higher values are observed from March to June, while lower values occur from August to December. The variations between these two seasons are very high.
For the CO_2 emissions, an emission factor α_H of 2 g/kWh.

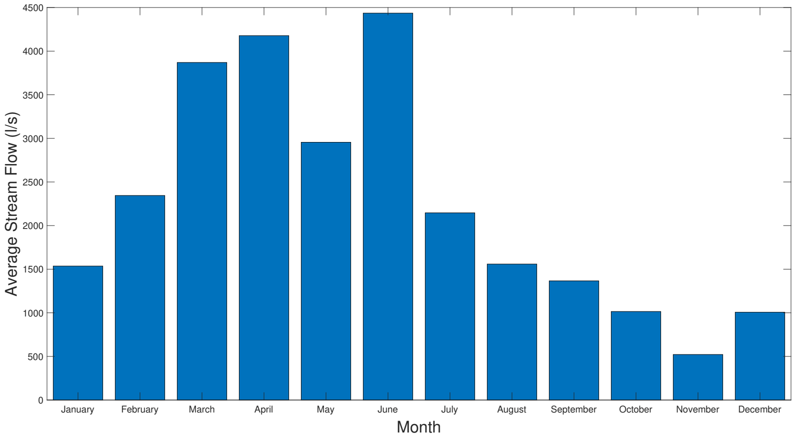

Figure 5: Monthly Average Micro Hydro Stream Flow.

4.4 Diesel Generation

Since RE presents fluctuating characteristics, a microgrid requires fuel generators, electricity storage, or both to guarantee constant power supply is a stand-alone scenario in particular. Thus, two Generic 100 kW Fixed Capacity Generators are used for the model. Based on [41], a capital cost of 882\$/kW is assumed, with a replacement cost of 705.6\$/kW, and with total operation and maintenance costs of 0.3\$/op. hour.
In Ecuador, fuels are highly subsidized, and end-users pay just 23 % of the total fuel bill [42]. Diesel end-user price is 0.26 \$/l in Ecuador based on local quotations resulting in a real price of 1.13 \$/l [43]. Furthermore, the transportation cost has to be considered in the final fuel price. The transportation cost to these remote communities could be estimated to 0.30 \$/l [44]. Thus, the considered total real diesel price for the model is 1.43 \$/l.
HOMER calculates the CO_2 emissions based on diesel generation. The fuel consumption of the assumed generators is 0.289 l/kWh. Moreover, the diesel generators are assumed to have emission properties of 2.638 kgCO_2/l. This results in CO_2 emission factor α_D of 763.6 g/kWh.

4.5 Additional Input Constraints

In Ecuador, planning projects typically consider a discount rate r of 12% and inflation rate of 2%, which were also assumed for this model [41]. The considered planning horizon is 20 years.
All the costs for the long-term microgrid planning are summarized in Table 1.

Table 1: Costs for the microgrid planning

Options	Capital Cost	Replacement Cost	O&M Cost
Hydro	2,260 \$/kW	1,080 \$/kW	137.95 \$/kW/yr
Diesel	882 \$/kW	882 \$/kW	26.3 \$/kW/yr
PV	1,300 \$/kW	1,040 \$/kW	38.6 \$/kW/yr
Battery	300 \$/kWh	300 \$/kWh	10 \$/kWh/yr

5 Results and Discussion

For the case study, two microgrid configurations are studied. The first microgrid includes PV, hydroelectricity, diesel, and battery storage. The second one is similar but does not include diesel generation. These scenarios were selected to evaluate a possible carbon-free microgrid. For each configuration, the least-expensive configuration of each generation or storage component is optimized by HOMER.
The proposed two microgrid configurations that were built in HOMER are illustrated in Figure 6.

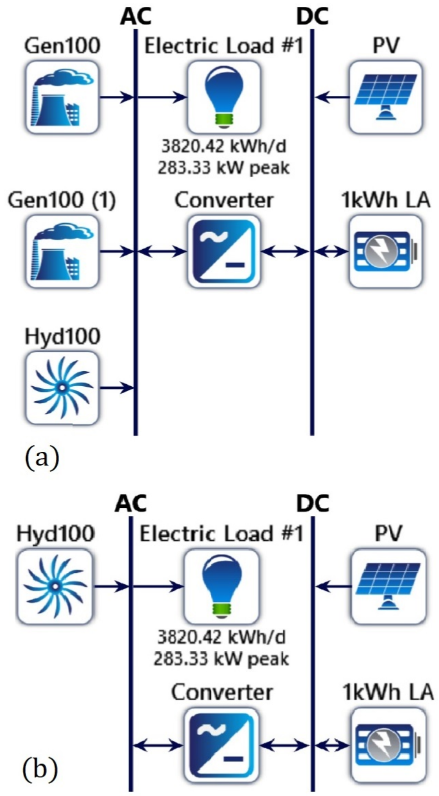

Figure 6: Microgrid configurations of the two simulated HOMER models: (a) PV/Hydro/Diesel; (b) PV/Hydro.

During the planning horizon, diesel price is uncertain due to the typical price fluctuations. Thus, a sensitivity analysis was carried out, considering various assumed diesel prices in the time horizon. It is assumed an increase of the average diesel price in either 50% or 100% during the 20 years, as per [41]. The transportation cost is the same as 0.30 \$/l, which results in final diesel prices of 2.00 \$/l and 2.56 \$/l, respectively.

5.1 Economic and Environmental Analysis

The economic and environmental results for the optimal two configurations are summarized in Table 2 considering the actual diesel price of 1.43\$/l. Note that the configuration with Diesel Generation results in a much lower NPC compared to the configuration without Diesel Generation. This could be ex-

Table 2: Microgrid characteristic results for the two studied configurations

Case	PV/Hydro/Diesel	PV/Hydro
NPC [M\$]	2.33	7.93
COE [\$/kWh]	0.194	0.660
Capital Cost [k\$]	719	5,523
CO_2 [Ton/yr]	269.0	192.5
PV [kW]	112	2,240
Storage [kWh]	470	7,950
Hydro [kW]	100	100
Diesel [kW]	200	0

Table 3: Microgrid characteristic results considering different diesel prices

Diesel Price [\$]	1.43	2.00	2.56
NPC [M\$]	2.33	2.79	3.55
COE [\$/kWh]	0.194	0.232	0.295
Capital Cost [k\$]	719	779	1,650
CO_2 [Ton/yr]	269.0	248.6	161.2
PV [kW]	112	165	422
Storage [kWh]	470	540	2,340

plained because the PV is relatively expensive, does not generate enough electricity only during the day, so an important investment in PV and storage must be performed to replace diesel generation.
Although the configuration PV/Hydro results in only 192.5 Ton/yr emissions of CO_2, the NPC and COE are too high, so the investors cannot be confident in investing in such configuration.
In Table 3, the economic and environmental results for the microgrid with PV/Hydro/Diesel are shown considering the different diesel prices in the planning horizon. For all the cases, the COE is relatively low, considering that the microgrid should be in a remote community. Furthermore, an increase in diesel price leads to an increase in PV and battery investments, and thus a decrease of CO_2 emissions.

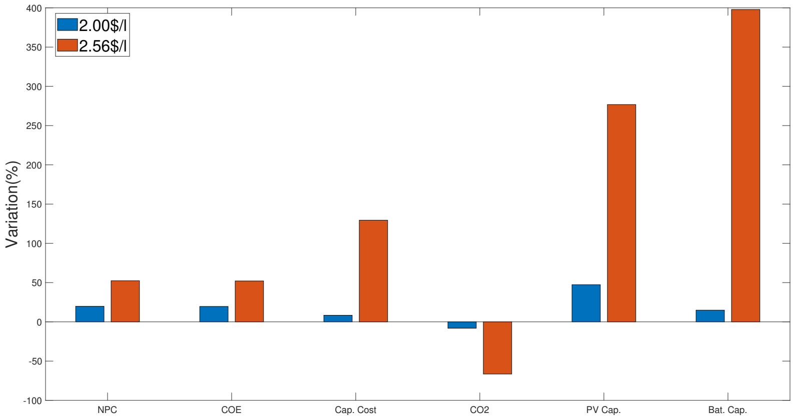

Figure 7: Economic and environmental variables variations considering various diesel prices.

5.2 Energy Supplied

To highlight the variations of the diesel prices, Figure 7 depicts the percentage variation of the economic variables of the diesel prices of 2.00\$/l and 2.56\$/l compared to 1.43\$/l, which is the actual value. The PV and battery have significantly been increased with a diesel price of 2.56\$/. In Figure 8, the amount of energy supplied by source is illustrated.

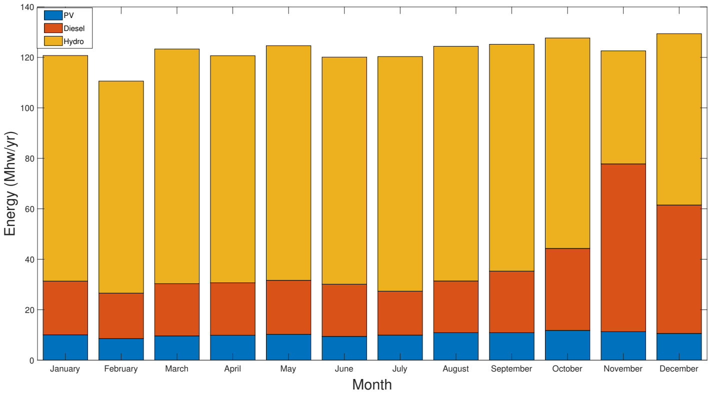

Figure 8: Monthly energy supplied by generation source.

In Figures 9 and 10, the monthly Box and Whisker plots of Diesel and PV electrical power output are depicted. Note that in November, diesel electrical output has a significant growth due to the low Stream Flow of November, resulting in a decrease of the hydro electrical energy.

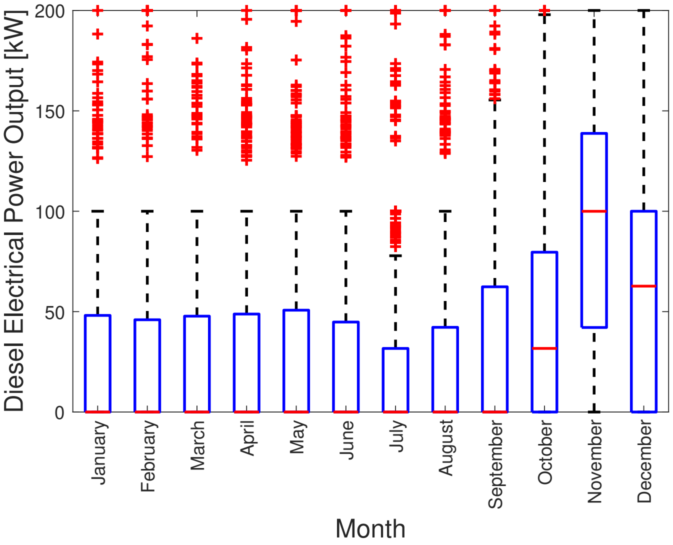

Figure 9: Monthly boxplot of the Diesel Electrical Power Output.

5.3 Daily Operation

To assess the daily operation of the two proposed configurations, Figures 11 and 12 depict the power generation patterns of diesel, PV, micro hydro, battery output, and the load. Seven days were selected corresponding to November 13^th to November 19^th, when the river's streamflow is low to highlight PV and diesel generators' operation. In Figure 11 it is observed that the baseload is meet by micro hydro generation. The rest of the load is met by PV during the day and diesel generation and energy storage during the night. Note that in the two last days, the PV output is minimal (due to the absence of solar irradiation), and a more considerable amount of diesel energy needs to be supplied. Moreover, for this configuration, the battery output is minimal since there is no RE generation excess.

In Figure 12 it is observed that the base load is also met by micro hydro generation. However, significant peaks could be observed all the days, especially the first days. The PV generation exceeds by a large amount the load, so it is stored in the battery storage to meet the load during night periods, where

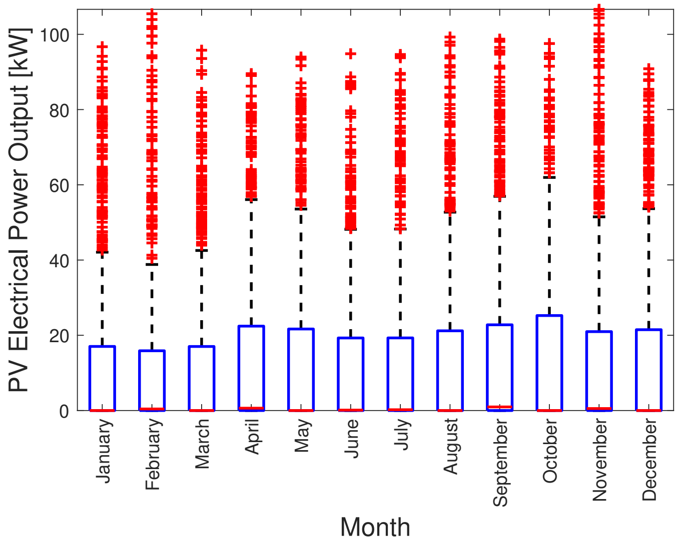

Figure 10: Monthly boxplot of the Diesel Electrical Power Output.

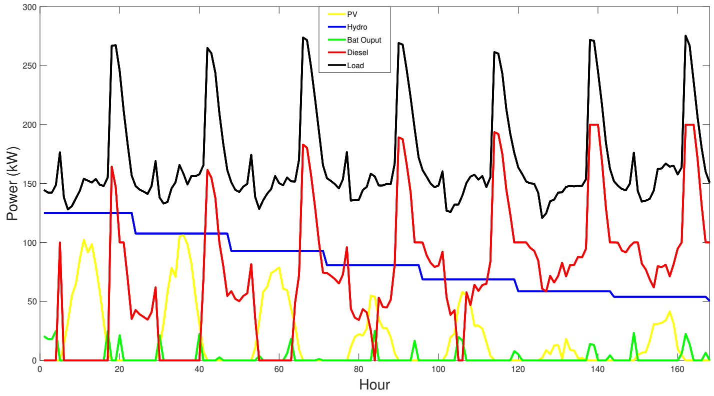

Figure 11: Generation and load profiles for the configuration PV/Hydro/Diesel.

the micro hydro power is not enough. Since the PV generation is exceptionally uncertain, one can assume why it is necessary to invest in a large capacity o PV, since on day 6 of the figure, it could be observed that the PV generation is small. It cannot meet all the required load, so previous energy should be stored in the batteries.

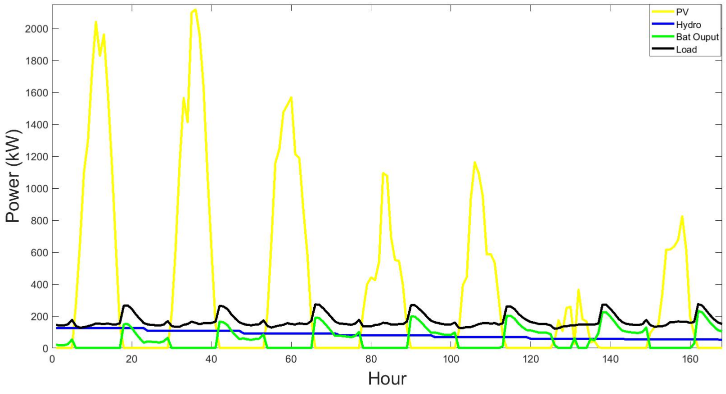

Figure 12: Generation and load profiles for the configuration PV+Hydro.

To evaluate the uncertainties of diesel prices in the future, Fig 13 illustrates the generation and load profiles of the same week of the configuration of PV/Hydro/Diesel, with a diesel price of 2.46$/l, which is the highest electricity price of the sensitivity analysis. Note that the configuration PV+Hydro is not influenced by the variations of diesel prices. It is observed that the PV generation is in excess in several periods, but the peaks are not excessively high. Diesel generation is only used on the days where PV generation is low. Moreover, it can be noted that diesel energy is lower than diesel price of 1.43$/l since it is optimal in terms of costs to consume less diesel.

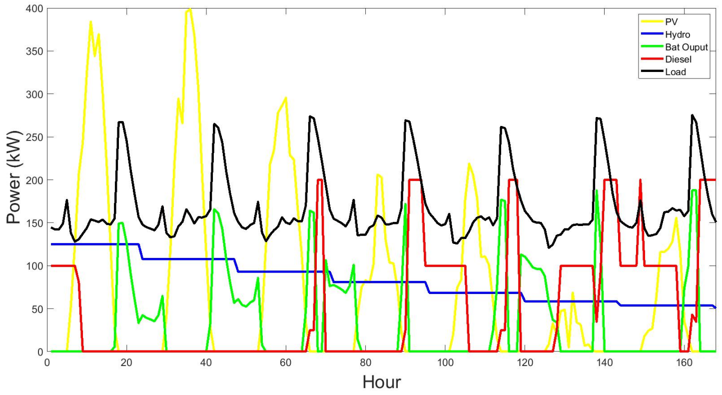

Figure 13: Generation and load profiles for the configuration PV/Hydro/Diesel and 2.64$/L diesel.

The yearly PV output for the PV/Hydro/Diesel configuration is illustrated in Figure 14. There is no season influence during all year, and there are positive values in hours 6 to 18 that are related to sunny hours in Ecuador.

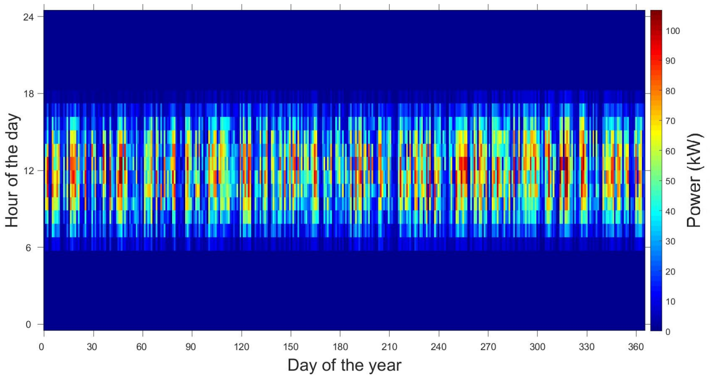

Figure 14: Yearly PV Output

Diesel power output is illustrated in Figure 15. Diesel generation usually works at night periods, where there is no PV generation, and when micro hydro power is not enough to meet the load. At the end of the year, diesel generators deliver more energy to mitigate micro hydro power's lower values during these periods.

Figure 16 depicts the yearly battery power output. This power output is observed in the periods of the night to give a support to diesel generation.

5.4 Discussion

In this work, real existing data, such as load, PV, diesel, and micro hydro generation, was used in HOMER Energy Pro. In addition, the more volatile data, which is the diesel prices in the 20-year planning horizon, is considered in the model. Thus, the results can be assumed to be accurate enough.

Various other inputs could be considered in the uncertainties in the model, such as the volatility of the PV costs with time. However, the *NPC* result variations are minimal since other costs should be consid-

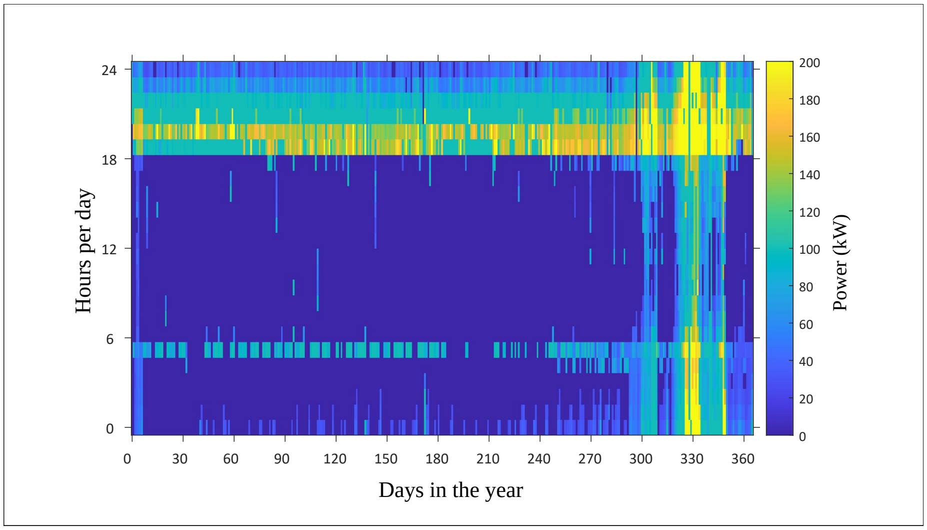

Figure 15: Yearly Diesel Power Output

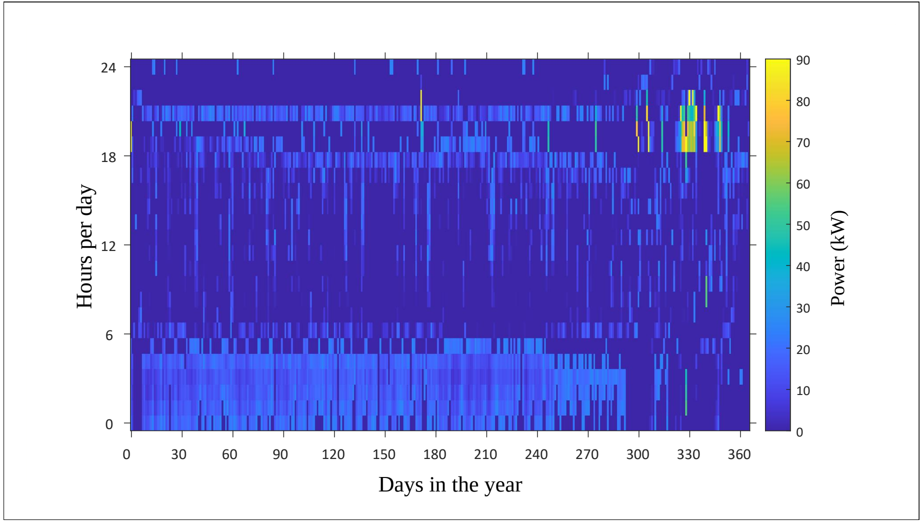

Figure 16: Yearly Battery Power Ouput.

ered in the total PV costs, such as the installation and logistics (e.g.:transportation to the remote communities), which do not vary with time.

Observe that many other works referred to in the literature review use data from available sources, such as IRENA [45]. This work intends to present accurate results considering real conditions of a case study, considering specific characteristics such as the load or assuming transportation and logistic costs for the various generation sources.

The results for the case of PV/Hydro/Diesel indicate a COE of 0.194\$/kWh, which is high for the Ecuadorian electricity tariff (that is around 0.10\$/kWh) [5]. Considering that the electrification is for a remote community, the COE seems fair. Note that at present, in other places in Ecuador, such as the Galapagos Islands, higher actual prices are observed (0.383\$/kWh). Thus, the proposal of a PV/Hydro/Diesel isolated microgrid could result in a proper solution for these remote communities and others.

The obtained results correspond to the objective of minimizing the NPC. Of course, they could significantly differ if a constraint of emissions is included in the model or if an emission penalty was considered. However, in real conditions, especially in developing countries, investors always select the most profitable option.

6 Conclusion

This paper presented a techno-economic assessment of RE-based microgrids in the Amazon Region in Ecuador. This study allows proposing new electrical alternatives for isolated communities. Two pro-

posed microgrid configurations were built and simulated in HOMER Energy Pro. The first configuration considers PV, hydroelectricity, battery storage, and diesel generation, while the second does not consider diesel to analyze a carbon-free microgrid.
The results reveal an NPC of 2.33 M\$ and a COE of 0.194 \$/kWh for the PV/Hydro/Diesel microgrid configuration, and an NPC of 7.93 M\$ and a COE of 0.660 \$/kWh for the PV/Hydro microgrid configuration. Thus, in terms of costs, the first solution seems the best for investors.
A sensitivity analysis was carried out on three different planned costs to take diesel price uncertainty into account in the planning horizon. An increase in diesel prices results in additional investment in PV generation and battery storage, which will reduce CO_2 emissions that would be environmentally beneficial for these kinds of places. The implementation of these microgrids in remote communities in Ecuador rely on the governments' eagerness to invest.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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