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A hybrid energy system based on renewable energy for the electrification of low-income rural communities

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Abstract. Electrification of low-income rural areas that have a limited connection or no access to electrical grids is one of the most demanding challenges in developing countries such as Peru. The international commitment to stop global warming and the reduction in the cost of renewable sources of energy have reduced the prices of fossil fuels in some cases. This has opened the way to the current research which proposes a hybrid energy system (HES) based on the use of renewable sources of energy. Therefore, a renewable electricity system (HRES) was set up at the village of Monte-Catache in the Cajamarca region, which is one of the poorest areas of Peru. Surveys and field studies were used to evaluate the socioeconomic characteristics, availability of renewable energy resources, and energy demand of this region. Potential energy sources were evaluated, and isolated photovoltaic systems with a battery bank were found to be the most appropriate according to the results obtained in the simulation with HOMER. This proposal constitutes an interesting contribution for future energy solutions in isolated and low-income rural areas.

1. Introduction

Electric power is considered to be a variable for measuring the regional competitiveness of a country. At present, approximately 80% of the global demand for electric power is met by burning fossil fuels, which have negative impacts on the environment [1].

Conventionally, electric power in Peru is generated in thermoelectric and hydroelectric plants, following which the voltage is raised to a range of 110–480 kV to reduce losses in transmission systems during transportation, and eventually the power reaches the consumer via medium- and low-voltage distribution systems [2] [3].

Considering that 46% of the electric power in Perú is produced in thermoelectric plants and given the proven correlation of fuel combustion with greenhouse gases, renewable energies in electricity and hydrocarbons are deemed a state policy and increasing their share in the electricity generation as a whole and also mitigating the effects of climate change must be sought after [4].

To address the obstacles related to conventional electrification methods and to meet the current energy demand, the development of hybrid energy systems (HES) based on renewable energy sources is an economical and eco-friendly solution.

Renewable energy sources are virtually so abundant that they could supply more energy than the current global demand [5] [6]. Despite this incredible growth potential, renewable energy sources have not been fully exploited because of barriers such as technological, economic, and resource availability.

In Peru, the cost of supplying electricity to rural towns is excessively high because of the difficulty of access, geographical dispersion, and in some cases their proximity to protected environmental reserves. This is why it is difficult to connect the towns to the existing electricity distribution grids. Therefore, both the initial investment and the high costs of operation and maintenance of the grids make it virtually impossible for citizens to pay for electricity.

Due to these facts, generation technologies based on local renewable energy—known as isolated systems—have become a suitable option for these regions. In recent decades, both technological improvements and government policies to promote the use of renewable energy resources have resulted in a significant reduction in costs, which makes the proposed electrification of remote populations through renewable isolated systems an economically viable alternative [7] [8] [9].

In Peru, according to Legislative Decree No. 1002, such government policies imply that daily delivery of electric load by the Committee of Economic Operation of the System, a variable cost of production equal to zero, accelerated depreciation for the purposes of Income Tax and early recovery of the General Sales Tax [10] [11] [12] must be prioritized. Moreover, in 2011, the Ministry of Energy and Mines passed the Electricity Short-Term Market Regulation to promote effective competition in the electricity generation market of Peru through the inclusion of projects based on renewable energy resources (RER).

However, providing a constant supply of energy is a difficult task for most RERs because of the intermittent and unreliable atmospheric conditions, to which the production of energy is directly related. Therefore, in an effort to overcome the production variability of renewable energy-based systems and to provide a reliable power supply, such systems can be complemented with non-renewable generation systems, known as hybrid electric systems.

2. State of the art

Vast research has been conducted on isolated HSE and hybrid electrical systems, which combine two or more types of renewable technologies (e.g. photovoltaic energy, wind-turbines, mini-hydro generators, biomass, etc.) [12].

Due to the reduced manufacturing costs, photovoltaic systems are becoming an economical and technologically viable option. Studies have compared different hybrid systems that include photovoltaic technology as the main source of energy and other sources (battery banks, wind-turbines, and microhydraulic systems) as backup systems because of the intermittent nature of the sun and little irradiation at certain times of the year [13] [14]. This study indicated that with an increase in demand, the solar/batteries model becomes more inefficient and requires the inclusion of new sources of renewable generation. Other research established that hybrid energy schemes are more sustainable in terms of supplying electricity to a rural center compared with isolated photovoltaic systems because of the lack of solar irradiation in the months of winter. This is due to the fact that trusting a single technology generally results in the oversizing of the system, which increases the initial capital cost of the plant.

The multiple combinations of renewable energy technologies with non-renewable sources, as well as the reliance on several factors such as the demand by population, the availability of renewable energy sources (RES), and the component costs, compound to the complexity of a proper design of these combinations [15]. The HOMER software models each system configuration by performing hour-by-hour simulations of the different technology options, component costs, and resource availability. Then, they analyze the technical feasibility of the configuration and calculate the total cost of the implementation and operation of the system. A summary of studies that used HOMER for the sizing of isolated systems and with relevant characteristics for this study is presented in table 1.

However, the research conducted has not delved into the impact of the cost of electricity in rural villages that are difficult to access. Therefore, the purpose of the research is to design an HES that will

meet the electricity demand of the population with the best available combination of RES and at the lowest cost possible to supply electricity in a reliable and sustainable manner [16] [17].

3. Proposed methodology

The proposed methodology is divided into five stages: selection of the village or community for the project, estimation of the energy demand of the populated center, determination of the optimal model for sizing the system, development of financial analysis, and implementation. These stages are represented in the flow chart in figure 1.

Table 1. Summary of important studies of isolated power generation systems.

Authors	Technology considered	Types of needs met	Sensitivity variables	Important topics
Beck and Schott [10].	•Small hydroelectric plants, wind-turbines, photovoltaic solar units, bio-diesel generators	•Domestic •Commercial and industrial •Medical Center •School	•Biodiesel price •Wind speed •Design flow	•Pre and post HOMER analysis
Hafez and Bhattacharya [3].	•Only diesel, fully-renewable, mix of diesel and renewable, connected to the external network	•Domestic thermal and electrical needs of a hypothetical rural community	•Diesel price, shortage of maximum allowable capacity	•The importance of an unmet load
Lee, Soto and Modi [15].	•Solar photovoltaic units	•Conservation of domestic and community food	•Not considered	•Algorithm to measure energy deficit •Probability
Ma, Yang and Lu [14].	•Solar/Wind Hybrid	• Hypothetical load of 250 kW h/day	•Solar Radiation •Wind speed •Photovoltaic, wind and battery capacity	•The importance of combining the demand for power and generation to minimize the dumping energy
Murphy, Twaha and Murphy [16].	•Diesel, solar energy, Solar-diesel hybrid	•Hypothetical loads	•Not considered	•Cost of reliable electricity and modeling a reliable grid
Alzola et al. [17].	•Photovoltaic solar energy, wind-turbines	•Domestic, industrial loads, water pumping loads	•Lack of capacity	•Framework study for calculating energy demand
Patil, Saini and Sharma [18].	•Micro-hydraulic energy power, photovoltaic solar energy, biomass gasification, and hybrid systems	•Domestic agriculture •Community •Rural industries	•The cost of biomass fuel	•Reliability parameters

3.1. Selection of the adequate community/village for the project

The first step in estimating energy demand is the formulation of criteria for the selection of the village or community. The framework for energy demand assessment developed by Camblong was used, and the selection criteria are as follows:

- No connectivity present to the grid and relative long time for future grid connectivity.
- Degree of grouping of dwellings.
- Presence of telecommunications towers.
- Presence of premises and small business that require energy.

3.2. Calculation of electricity demand

Calculation of the demand for electricity in small rural villages is based on their maximum power demand. For this, the energy demand method was developed, and it requires the following information about the activities of the populated center [18] [19].

- Activities in the home; times of going to bed and wake up, food preparation, etc.
- Commercial and industrial activities: agriculture, commerce, tourism, etc.
- Public services: schools, telecommunications, health, weather and sanitation.

The information obtained is recorded in the format described in table 2, and the power demand is a result of the power of the electrical equipment (P), the simultaneity coefficient (SC), and the number of users (No.) as is shown in equation 1. Thus, the total of the potential demand in a period will be the sum of all the potential demands by the village.

$$Dp = P \times CS \times N^c \qquad (1)$$

3.3. Determination of the optimal model for sizing the system

For this purpose, several software techniques, and optimization methods exist to maximize/minimize the objective functions according to the constraints of the HES; however, all of them require the following data as input [20]:

3.3.1. Weather data. Information on wind speed, solar radiation, temperature, and speed of the village flow was collected to calculate the power output of the system**.**

3.3.2. Energy load required. The energy load or demand by the population is the most important factor to make simulations and optimize HES because these elements restrict the design of HES. This can be determined with existing data, forecasts, or field studies.

3.3.3. Characteristics of the equipment. The efficiency of the operation was determined by the characteristics of the equipment used in the HES. For this purpose, a table indicating the main characteristics such as power and voltage was used.

3.3.4. Search space. The HES involves diverse equipment and technology; therefore, certain degrees of slack must be considered in the simulation.

3.3.5. Economic data. For the case studied, various systems were used such as wind-turbines, photovoltaic panels, microhydraulic turbines, diesel generators, and battery banks, which are presented in a table that identifies their technical characteristics and initial capital costs, maintenance, and operation of the useful life of the HES.

3.3.6. Technical data. Technical data are required such as distribution strategies and operational reserves.
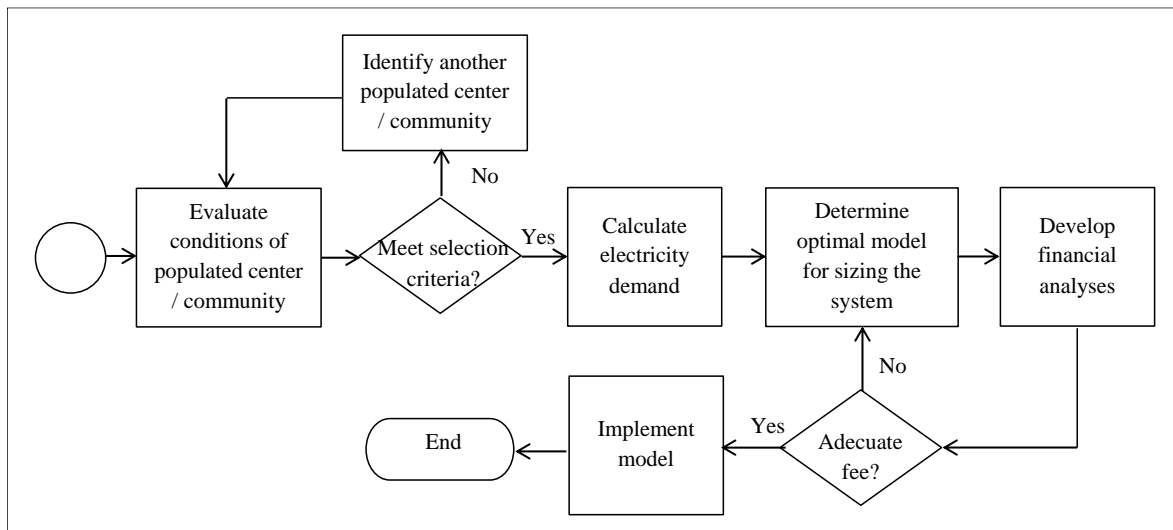
Figure 1. Proposed methodology for the implementation of a renewable HES

3.4. Financial analyses

The financial analysis comprises determining the period for recovery of the investment, which is the period of time required for the net cash flow of the investment to be recovered till their initial value. For this, the net cash flow of the project was set, and the initial investment of the project was estimated in period zero. The cash flow corresponding to the following periods is described in table 3.

Finally, the period in which the total investment was recovered was counted to determine the investment recovery term.

Table 2. Form for the evaluation of the current electricity demand of the village

Utility	Power (W)	SC (%)	No.	Hours of use	kWh Day	kWh Year
Residential						
Lighting	40,0	50%	100,0	4,0	8,0	2.920,0
Food preservation	400,0	98%	1,0	5,0	2,0	715,4
Recreation and amenities	300,0	50%	25,0	3,0	11,3	4.106,3
Other uses	1.300,0	50%	25,0	1,0	16,3	5.931,3
Total residential	2.040,0				37,5	13.672,9
Industrial and commercial						
Motors	5.000,0	2,0	8,0	40,0	14.600,0	2,0
Refrigerators	1.000,0	2,0	8,0	8,0	2.920,0	2,0
Ovens	0,0	0,0	0,0	0,0	0,0	0,0
Lighting	40,0	30,0	8,0	4,8	1.752,0	30,0
Others	3.000,0	30,0	8,0	360,0	131.400,0	30,0
Total industrial and commercial	9.040,0			412,8	150672	
Public services						
Health	2.500,0	100%	1,0	16,0	40,0	14.600,0
Education	3.000,0	100%	1,0	8,0	24,0	8.760,0
Communications	3.000,0	100%	1,0	8,0	24,0	8.760,0
Street lighting	2.750,0	100%	1,0	8,0	22,0	8.030,0
Other public services	2.000,0	100%	1,0	16,0	32,0	11.680,0
Total public services	13.250,0				142	51830
Total	24.330,0				592,3	216.174,9

4. Description of the selected rural area, components and scenarios

4.1. Selection of the populated center

In Peru, of the 3 million Peruvians without access to electricity, 78% come from rural areas. According to the General Directorate of Rural Electrification, Cajamarca is the region with the lowest coefficient of electrification because only 55% of the population has access to electricity [21]. Factors such as the climatic, geographical, economic, and cultural features, as well as the political context of villages, are the causes of the low degree of electrification observed. One of the districts of this affected region is the district of Catache, in the province of Santa Cruz, which auctioned the electrification project for its rural areas in 2008 and included 21 villages. The the village of El Monte (latitude: −6.6758°, longitude: −79.032016°) was chosen because of the presence of RES and its difficult access to existing distribution grids.

4.2. Calculation of energy demand

The results of the surveys state that 30% of houses in the village hold trade activities; this is why the use of household appliances and lamps is high, while the remaining 70% houses are used as dwellings. This reduces their electrical consumption to only two (02) lamps and audiovisual equipment. [22] [23] [24]. The load profile is obtained via the form shown in table 2.

4.3. Weather data

The historical database of the National Meteorology and Hydrology Service of Peru (SENAHMI) and the coordinates of the village were used to determine the average values of solar radiation and wind speed, as shown in figures 2 and 3, respectively. The flow velocity of the Carhuaquero River was calculated using the equations developed by Beck and Schott and presented in figure 4.

Table 3. Net flows of the project

	Year	0	6	7
Cost	Soles/kWh	0.62	1.85	2.22
Annual cost village	kWh		8,491	8,576
Total investment	Soles/house	-347,432	-	-
Income			66,058	72,431
Sale of energy	Soles		13,100	15,877
Fixed monthly charge per house	Soles	7.07	205.09	205.09
Cost of installation for supply	Soles	500.00	-	-
CO_2 credits	Soles/ tCO_2	28.95	1,613.61	1,629.75
Social benefit to the population	Soles	-	51,139	54,719
Costs (Operation Maintenance cost)	Soles		−131.00	−158.78
Expenses			−1,084	−1,139
Profit before income tax		-	63,626	69,835
Profit after income tax		-	63,626	69,835
Economic flow		347,432	63,626	69,835

Net financial flow	347,432	63,626	69,835
Cumulative flow	347,432	−42,758	27,077

4.4. Characteristics and economic data of the equipment used
Considering the products available in the Peruvian market, a list of the components was selected and their prices were found through different national distributors and manufacturers. The selected components and their corresponding costs are shown in table 4.

4.5. Simulation and optimization of the system´s model
The tool used to optimize the sizing of the HES is the Hybrid Optimization Model for Electric Renewables (HOMER). HOMER software was used to achieve economic optimization of the different configurations for the El Monte community. To do this, six different scenarios were analyzed for the best possible configuration for El Monte: diesel generator (case 1), FV + batteries (case 2), wind turbine (case 3), solar/wind hybrid (case 4), solar + microhydraulics hybrid (case 5), FV + diesel hybrid (case 6) and solar + wind + diesel hybrid (case 7). Figure 5 shows the configurations of the scenarios in HOMER.

4.6. Financial analysis
The scenario chosen by HOMER was an isolated solar system with a battery bank (case 2) whose component cost is $347,432.00 Peruvian Soles. It was established that the payment by inhabitants for domestic consumption would be 0.62 Soles per kilowatt/hour, and this value that corresponds to the average cost in the region. In the first month a payment of 500 Soles will be made for activation of the service. Currently, on an average, each family spends 104.00 Soles per month on inefficient energy sources such as kerosene and candles. With these costs, the recovery period of the isolated solar electric system and batteries is 6.61 years.

5. Description of the selected rural area, components and scenarios
Figure 6 presents the costs of each configuration modeled using HOMER. The case 2 has photovoltaic panels supported by battery banks and meets the energy demand of the farm with the lowest cost per kW/h: 0.62 Soles kW/h. This increases the probability that 100% of homes can access the electricity supply service. Additionally, this configuration presents one of the lowest operating costs (26,151 Soles/year) because of the technology used.
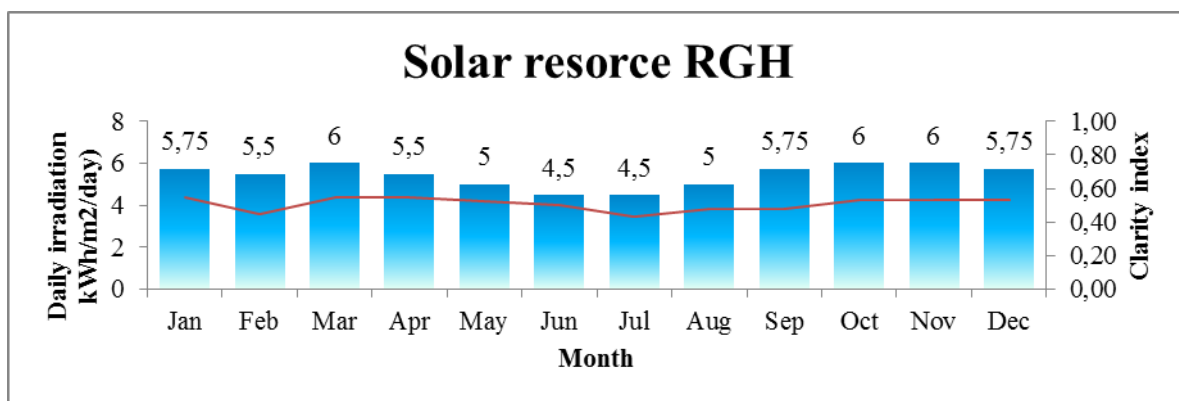

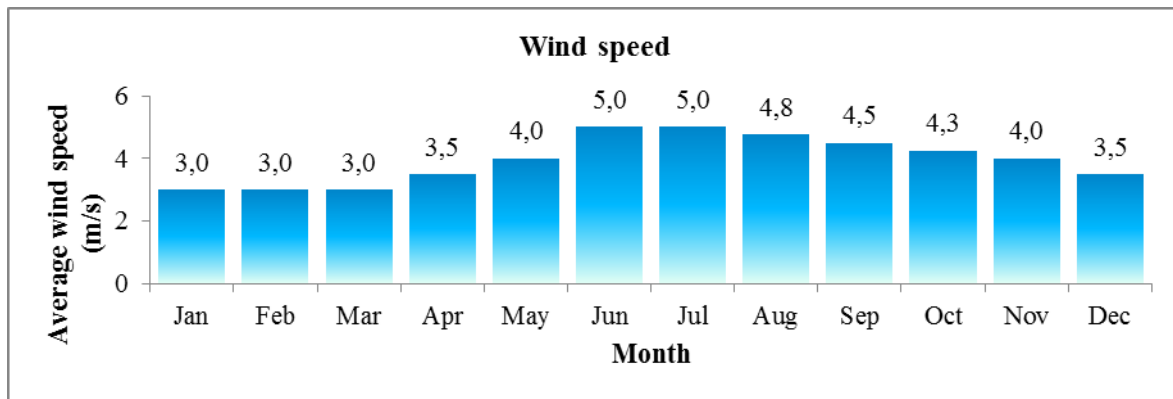**Figure 2.** Average solar irradiation in El Monte Village, 5.38 kWh/m2

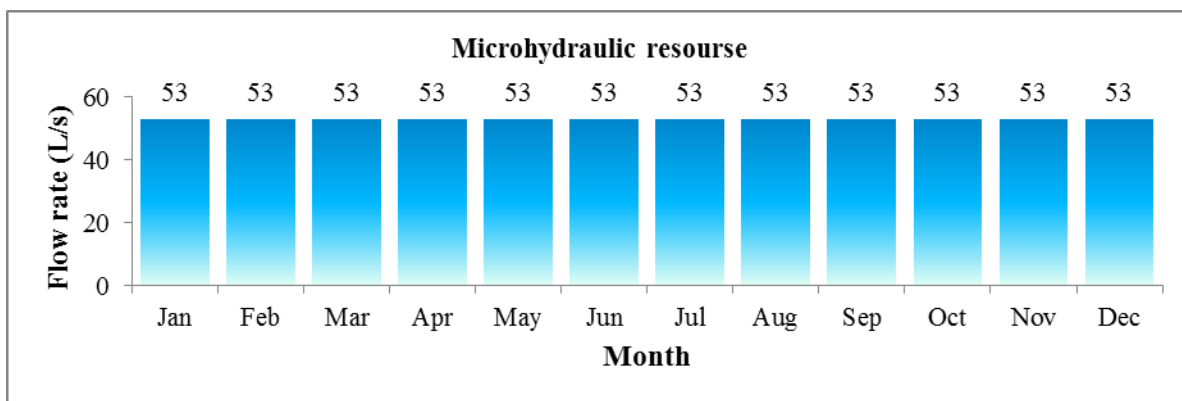**Figure 3.** Average wind speed in El Monte Village, 3 m/s

Figure 4. Carhuaquero river flow rate in El Monte Village, 53 L/s

On the contrary, case 3 presents the highest cost of kW/h in the simulation (1.65 Soles kW/h), and this confirms that relying only on a renewable energy technology results in a high cost of electric power because of the oversizing of the system and the high initial investment costs of the wind-turbines.

Case 4 was simulated numerous times because in seasons where there was less solar irradiation, wind speed was usually higher, which makes it an efficient system. However, for the case study, the wind speed was only 3 m/s, so there was an oversizing in panels to meet the demand, which translates into a higher initial cost (633,017 Soles).

Table 4. Characteristics of components and costs

Component	HOMER suffix	Model	Characteristics		Capital cost (Soles)	Operation and maintenance cost (Soles)
Wind turbine	AH10	AEOLOS - H 10kW 3 blades	Average power: Rotor diameter: Wind speed: Noise: Height:	10 kW 8 meters 10 m/s 45 db 12–18 m	93.000,00	24.64
Micro hydro turbine	TURBINE	MONO FLOAT 3 blades	Power: Rotational speed: Weight: Rotor diameter	250–5000 W 90–230 rpm 380 kg 1000 mm	47,820.00	1,460.00

Photovoltaic panel	FV	HONEY 60-cell module	Power: Maximum efficiency: Maximum tension:	265–280 W 17.1% 30.8 V	2,000.00	2,025.00
Inverter	INVERTER	Isolated system inverter	Voltage: Power: Output voltage:	10.5–15 V 300 W 210–240 V	15,000.00	14,400.00
Battery	H3000	Stationary battery	Capacity: Temperature:	3000 Ah −20°C–45°C	7,380.00	7,117.00
Diesel Generator	Generator	Gasoline generator set	Average output: Voltage: Motor power:	10 kW 110–220 V 20 HP	20,400.00	17,000.00

It is thus proven that it is possible to design an HES that can guarantee electricity access to the rural populations without access to the energy distribution system, and this HES is economically sustainable.

6. Impacts

6.1. Economic impact
As defined in the financial analysis, the cost will be 0.62 Soles /kWh as seen in table 3. The expense is 104.75 Soles/month. When compared against the renewable system, the former system would cost approximately 5.58 soles/month, after the first month in which a payment of Soles .500 is made to activate the service.
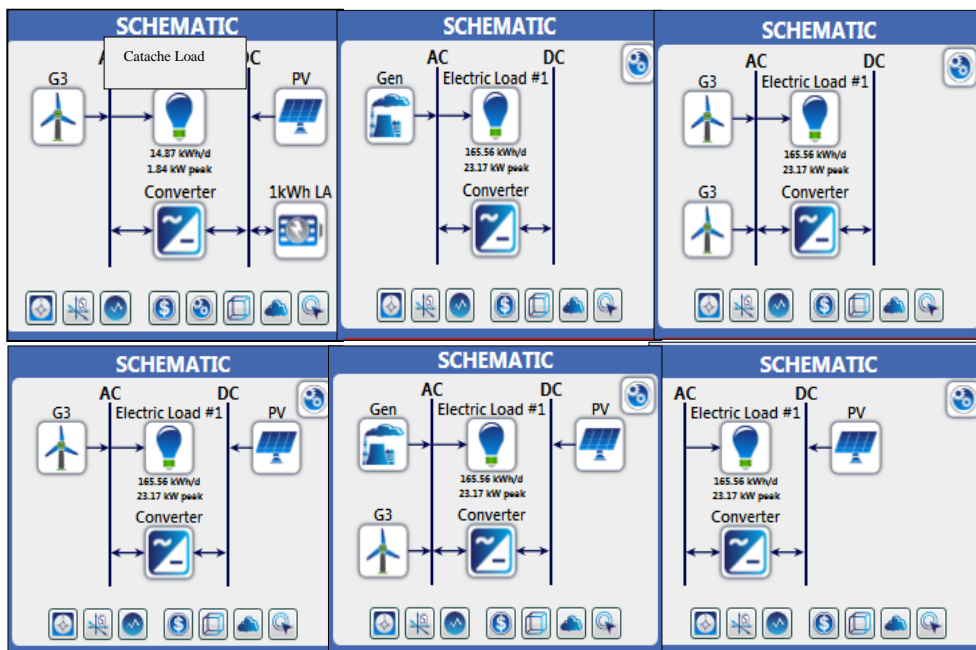

Figure 5. Sets of isolated configurations analysed using HOMER

6.2. Social impact
For the development of projects with a considerable social impact such as rural electrification, community participation is an active process where users not only receive the benefits of the project but also influence the direction and execution of the project.

6.2.1. Social and cultural sustainability in renewable project. Socio-cultural and political issues are part of the earliest stage of project development; for example, the careful selection of users and the appropriate mode of communication with different segments of a community will determine the level of success that a program can hope to achieve. It should not be assumed that a community requires a particular technology and that they will accept it as soon as they have access to it. The introduction of new technology can generate different reactions in different communities**.**

6.2.2. Focus on the energetic needs of users. The demand for energy technologies in rural areas goes through a long range of problems in which supplying lighting needs is only a part of the scenario. A successful rural electrification program should allow the diversified application of this energy, including money income, entertainment, and education.

6.2.3. Understanding the community. The first step to involve the community is to understand it because the level of participation in a project depends on the context in which it happens. Context may include, for example, population, economic conditions, religious traditions, health, and nutritional benefits, and these factors vary depending on the country. The appropriate development strategies in one country are not necessarily appropriate in another because the context differs.
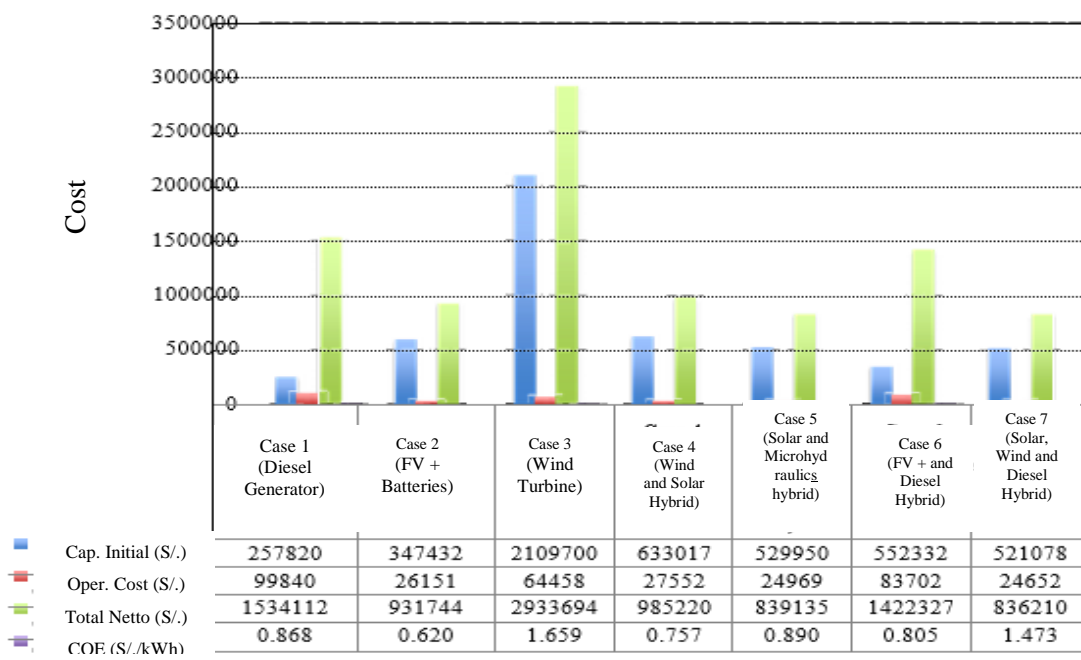

	Case 1 (Diesel Generator)	Case 2 (FV + Batteries)	Case 3 (Wind Turbine)	Case 4 (Wind and Solar Hybrid)	Case 5 (Solar and Microhydraulics hybrid)	Case 6 (FV + and Diesel Hybrid)	Case 7 (Solar, Wind and Diesel Hybrid)
Cap. Initial (S/.)	257820	347432	2109700	633017	529950	552332	521078
Oper. Cost (S/.)	99840	26151	64458	27552	24969	83702	24652
Total Netto (S/.)	1534112	931744	2933694	985220	839135	1422327	836210
COE (S/./kWh)	0.868	0.620	1.659	0.757	0.890	0.805	1.473

Figure 6. Systems of associated costs for each configuration

7. Conclusion

The design of an HES has been presented to provide electricity to a population that has difficult access to electricity and is not connected to a power grid. This strategy is based on global engineering systems stipulated by the IEEE and best practices.

The cost per kW/h achieved by the HES was 0.620 Soles, which equals the cost of electricity supply offered by the conventional grid. This means that such cost is competitive in the market and has the potential to reduce its costs due to the technological improvements and to the population growth expected, because more than 80% of the costs of implementation of the HES are fixed costs.

The solar-hybrid and battery combination is the most profitable for remote rural areas and allows

a period for recovery of the investment. However, the cost analysis shows that an increase in energy demand would make the solar microhydraulics and battery bank scenario the most optimal.

It is estimated that the amount of emissions will be reduced by 87,852 $kgCO_2$-eq/KWh for the generation of 228,186 KWh in a period of 25 years. Therefore, it is recommended that future research is conducted on the relationship between the implementation of the HES and the environmental conditions to be faced by populations from these rural areas in the coming year.

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