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# Energy optimization for rural communities: an integrated approach to hybrid PV/Battery/Diesel systems

# Optimización energética para comunidades rurales: un enfoque integrado de sistemas híbridos de PV/baterías/diésel

Jhon Jhonathan Peñalva-Sánchez[1], Jaime Eulogio Luyo-Kuong, Juan Peralta-Jaramillo[2], José Carlos Álvarez-Merino[3]

[1]Posgrado, Facultad de Ingeniería Mecánica, Universidad Nacional de Ingeniería. Avenida Tupac Amaru # 210 Rímac. Lima, Perú.
[2]Facultad de Ingeniería en Mecánica y Ciencias de la Producción, Escuela Superior Politécnica del Litoral. Kilómetro 30.5 Vía Perimetral, Guayaquil 090150. Ecuador
[3]Facultad de Ingeniería, Universidad Peruana de Ciencias Aplicadas. Prolongación Primavera 2390, Los Álamos de Monterrico, Santiago de Surco. Lima, Perú.

**ABSTRACT:** This study focuses on the design, simulation, optimization, and dispatch strategy of an off-grid hybrid PV/battery/diesel system to meet the annual energy demand of San Juan de Tarucani, Arequipa, Peru. It has been carried out using the HOMER program, and the results obtained highlight an optimal operation of the proposed system having a low Net Precent Cost, Cost of Energy, and a high percentage of a renewable fraction compared to the photovoltaic system supported only with battery. The energy production of the proposed system covers all the energy consumption of the place with excess energy of 40.1% during the year and minimum participation of the diesel generator, indicating the great potential of the solar resource of the place. The optimal Load Following dispatch strategy describes the energy flow of the system showing the participation of each generator on the day. Finally, the environmental impact of the system with and without a diesel generator is compared based on the amount of emission of pollutants in the environment throughout the year.

**RESUMEN:** Este estudio se centra en el diseño, simulación, optimización y estrategia de despacho de un sistema híbrido PV/batería/diésel fuera de la red para satisfacer la demanda energética anual de San Juan de Tarucani, Arequipa, Perú. El mismo se ha realizado utilizando el programa HOMER y los resultados obtenidos resaltan una óptima operatividad del sistema propuesto teniendo un bajo *Net Precent Cost, Cost of Energy* y un alto porcentaje de fracción renovable comparado con el sistema fotovoltaico apoyado únicamente con batería. La producción de energía del sistema propuesto cubre todo el consumo de energía del lugar con exceso de energía del 40.1% en todo el año y una mínima participación del generador diésel, indicando el gran potencial del recurso solar del lugar. La optima estrategia de despacho del tipo *Load Following* describe el flujo de energía del sistema mostrando la participación de cada generador a lo largo del día. Finalmente, el impacto ambiental del sistema con y sin generador diésel es comparado mediante la cantidad de emisión de contaminantes en el ambiente en todo el año.

**KEYWORDS**
Renewable energy sources; solar radiation; rural communities; solar power stations
Fuentes de energía renovable, radiación solar, comunidades rurales, centrales solares

## 1. Introduction

Recent technological advancements and population growth have significantly increased electricity demand, widening the gap between supply and demand [1, 2]. Much of the world's electricity generation comes from fossil fuel resources. These resources cause many problems in the environment, such as environmental pollution and global warming, due to the emission of carbon dioxide ($CO_2$) [3]. Therefore, it is of great importance to satisfy the growing energy demand by using energy generation sources that are environmentally friendly and take advantage of local natural resources, which allow a reduction in the consumption of fossil fuels in power generation and avoid environmental pollution that affects the planet.

From this perspective, renewable energy sources can not only contribute to sustainability but also strengthen the development of distributed generation systems, enabling the installation of energy production systems closer to consumption sites. Recent advances in the development of renewable generation technologies use natural resources (wind, solar, and others) for the efficient production of electricity [4].

Renewable energies have a lower impact on the environment than other energy sources; however, their performance is conditioned in most cases by meteorological and climatic variations [5]. On the other hand, when a generation system (photovoltaic or wind) is used with its renewable resource to supply electric energy to isolated places, many problems are encountered due to the intermittency and uncertainty of its resource, causing high investment and maintenance costs, and insecurity to cover the demand load of the place [2,5]. One of the possible alternatives to solve the problem of the intermittency of renewable energy resources and the increased use of this type of generation is to study the space-time complementarity by creating an energy mix [6,7].

The energy mix consists of the combination of renewable energy sources with other generation sources (such as conventional diesel and energy storage systems), also called Hybrid Energy Systems (HES). This system provides stable and reliable electricity to the power supply, as it combines energy generations efficiently [8]. HES offer many advantages that lead to the reduction of the Cost of Energy (COE) and the reduction of greenhouse gas emissions ($CO_2$, $NO_2$, among others), as well as increased operability of sources with renewable energy resources and allow access to electricity in rural and remote areas [9,10]. These advantages are in line with three of the central axes of Sustainable Development (SD), which are the care of the planet, people and prosperity [11]. HES are a suitable option that will promote local development in rural areas [12], where there are problems of connection to the electricity transmission grid, due to geographical barriers and climatic conditions.

Previous studies have investigated the optimization of renewable energy systems to meet the energy demand of rural off-grid communities: Bonkoungou *et al.* [13] evaluated the performance of a hybrid photovoltaic (PV) and battery system to meet the energy demand of a remote village in Burkina Faso, West Africa, using an Ant Colony Optimization (ACO) algorithm under the constraint of Loss of Power Supply Probability (LPSP). The research determined that the hybrid PV/battery system was a superior solution, leveraging the abundant solar energy at the site and producing lower pollutant emissions compared to diesel or photovoltaic-diesel systems.
Similarly, Rehman *et al.* [14] studied the reliability of a hybrid photovoltaic system coupled with wind and diesel generators to meet the electricity consumption of a village in southern Pakistan. Their results indicated that the proposed hybrid system was a viable solution for providing reliable energy, achieving a 69% reduction in greenhouse gases and a COE of $ 0.45/kWh, with a renewable penetration of 84%.
In turn, Gbadamosi *et al.* [15] conducted an optimization analysis using the Algebraic Modeling Language for different configurations of a hybrid energy system consisting of photovoltaic, wind, batteries, and diesel to meet the energy demand of sanitary facilities in a rural community in Nigeria. This study focused on system optimization aimed at minimizing pollutant gas emissions and the operating cost of the diesel generator. The study concluded that the combination of the four components was the most optimal configuration, with the lowest energy cost and diesel generator emissions.

Additionally, Rasool *et al.* [16] optimized the capacities of a hybrid (PV/Wind/Diesel/Battery) system using HOMER program to supply electricity to the rural community of Mander, in the Erbil governorate of Iraq. The simulation determined that the optimal configuration included a photovoltaic array of 74.7 kW, a diesel generator of 36 kW, a battery capacity of 124 kWh, and 13 kW of wind turbines. This optimal system showed a Net Present Cost (NPC) of $ 238,330 and a COE of $ 0.292/kWh, with a Renewable Fraction (RF) of 85.7 %. Furthermore, an alternative system (PV/Wind/Batteries) was evaluated, yielding an NPC of $ 297,593 and a COE of $ 0.365/kWh, with a RF of 100 %. The research emphasized the importance of photovoltaic solar and wind energy generation for rural communities in northern Iraq.

Similarly, Pazmiño *et al.* [17] conducted a techno-economic analysis of a hybrid photovoltaic generation system supported by diesel and batteries to supply electricity to rural communities in Bameno, Ecuador. This analysis, conducted using HOMER, resulted in the simulation of optimal system component sizing, with a COE of $ 0.359/kWh and a fuel price of $0.83 per liter, indicating that this system was the best option compared to a battery photovoltaic system.

Likewise, Hidalgo *et al.* [18] presented a technical, economic, and environmental analysis of a HES (diesel, batteries, photovoltaic) for an off-grid community in Bellavista, Ecuador, using HOMER to meet the energy demand. The study simulated fifteen system scenarios, considering three sizes of photovoltaic systems (8 kW, 10 kW, 13 kW) and five variations in diesel prices (from $ 0.26/L to $ 0.62/L). The results showed that systems with diesel generators were more viable with fuel prices below $ 0.35/L and made less use of batteries. However, for fuel prices above $ 0.35/L, the systems showed increased participation of photovoltaic and battery components. The study concluded that hybrid generation systems significantly reduce $CO_2$ emissions compared to using a diesel generator alone.

Also, Barrozo *et al.* [19] used HOMER software to simulate the operation of a hybrid system consisting of wind turbines and photovoltaic panels connected to the electrical grid, aiming to meet the total energy demand of Puerto Bolívar, Rancho Grande, and Nazareth in La Guajira, Colombia. The simulations revealed that the hybrid system in Puerto Bolívar made more efficient use of non-conventional energy resources. In contrast, Rancho Grande achieved higher system efficiency with a lower energy cost. The optimal system included 3 wind turbines, 441 photovoltaic panels, and had a NPC of $ 11.8 million, with low $CO_2$ emissions of 244 tons per year.

Finally, Muñoz *et al.* [20] simulated a combination of three hybrid generation systems (photovoltaic, wind, and hydroelectric) in the remote area of Riosucio, Chocó, Colombia. The optimal hybrid system configuration, backed by batteries, included a 100-kW photovoltaic array, 6 kW wind turbines, and an 800-kW hydroelectric generator, along with a chain of 300 batteries. This system had an NPC of $ 3,086,735 and a COE of $ 0.026/kWh, being the most economical compared to other evaluated combinations.

The objective of this research is to design and simulate a hybrid photovoltaic system that meets the energy demand of a rural community, considering the optimal capacities and lifetime of the system components, the minimum NPC and the minimum COE incurred by the system, and that the system obtains a high RF through the optimization of the HOMER program. Finding an optimal HES photovoltaic system that meets the established conditions will allow obtaining a reliable energy system between generation and consumption, as well as a cost reduction due to the combination of the system components and environmental sustainability, generating a reduction of pollutant gas emissions and taking advantage of the solar resource of the rural community.

This study contributes to the design and optimization of hybrid energy systems for rural electrification using photovoltaic energy, batteries, and diesel generators. By simulating different configurations with HOMER, we identify solutions that balance energy costs and emissions. Compared to previous studies, our results highlight the importance of reducing fossil fuel use and increasing renewable energy integration, offering a sustainable and reliable option for communities without grid access. This research provides a valuable foundation for advancing HES in rural areas.

This article is structured as follows: 1) the introduction, 2) the methodology where the procedures, climatic data, site consumption data, design and modeling of the hybrid photovoltaic system, as well as its techno-economic indicators and the HOMER program are mentioned, 3) optimization and simulation results, 4) discussion, and 5) conclusions.

## 2. Methods and materials

**2.1. Energy consumption and solar resource at the site of the study**

The micro power optimization model simplifies the evaluation of the off-grid and grid-connected power system for various applications [21]. So, a hybrid PV, diesel and battery energy system are designed for electrification in a rural town center. Tarucani is a populated center that is located in the central part of the district of San Juan de Tarucani, province of Arequipa. It is located in southern Peru at an altitude of 4,210 meters above sea level with coordinates of latitude 16 ° 11 'S and longitude 71° 3.6' E. The rural community of San Juan de Tarucani is considered in our research to design an isolated HES (Photovoltaic, battery and diesel). In this system, the potential solar resource of the place is evaluated, as well as the techno-economic analysis of its components, safety to cover the demand load and environmental impact. The district of San Juan de Tarucani has population centers and a community with a total population of 2,179 inhabitants and 945 houses in its various remote communities, according to the last census of the year 2017 [22]. As for economic activity, the population of San Juan de Tarucani is mainly dedicated to livestock, related to the raising of camelids, llamas and alpacas.

**2.1. Determination of electric load**

The load, which is determined considering the basic consumption of each house, schools and a health center, is introduced into Homer program for the graphic representation of the hourly and monthly load profile, as illustrated in Figures 1 and 2. The configuration on the random variable for 10 % day to day and 5 % hour to hour to day were used to enable the load to have some degree of variability at different times of the year. The average energy consumption is 165.80 kilowatt-hours per day (kWh/day), while the peak load over the year is 61.26 kilowatts (kW), with a load factor of 0.11. This data is shown in Table 1.

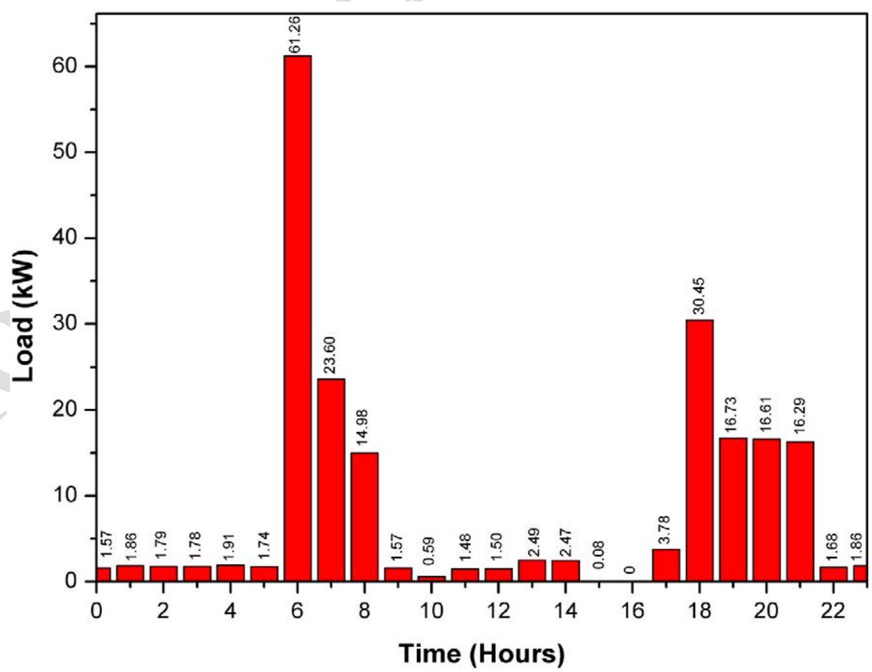


**Figure 1** Hourly load profile in San Juan de Tarucani

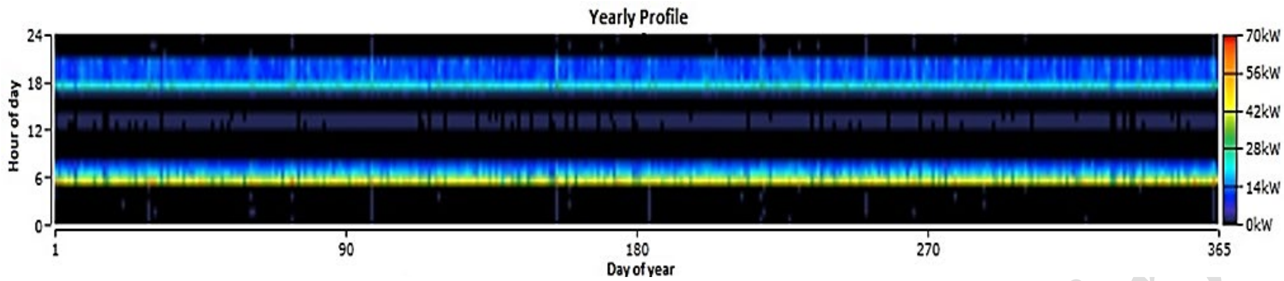


**Figure 2** Annual load profile of San Juan de Tarucani community

Table 1 Average load and peak of study area

| Metric | Details |
|---|---|
| Average | 165.80 kWh/d |
| Average | 6.91 kW |
| Peak | 61.26 kW |
| Load Factor | 0.11 |

## 2.3. Solar potential

The solar radiation data, clearness index and air temperature were acquired from NASA POWER "Prediction of Worldwide Energy Resources" using the latitude and length of the study location [23]. The solar and air temperature database obtained for the location of San Juan de Tarucani are used as information input to the HOMER program.

Figure 3 shows the daily radiation data, month and clarity index. The bar chart shows the monthly average daily solar irradiance (kWh/m$^2$/d), and the line graph indicates the clearness index for the community of Tarucani. The range of solar radiation is between 5.45 kWh/m$^2$/day to 7.94 kWh/m$^2$/day with an annual average of solar radiation of 6.71 kWh/m$^2$/day. It is found that the highest solar potential occurs in October and November with values of 7.94 Wh/m$^2$/day and 7.84 Wh/m$^2$/day, respectively. The lowest values are between the months of May, June and July with values of 5.85, 5.45 and 5.73 Wh/m$^2$/day. The average clearness index is 0.70 and the average air temperature is 14.74 °C.

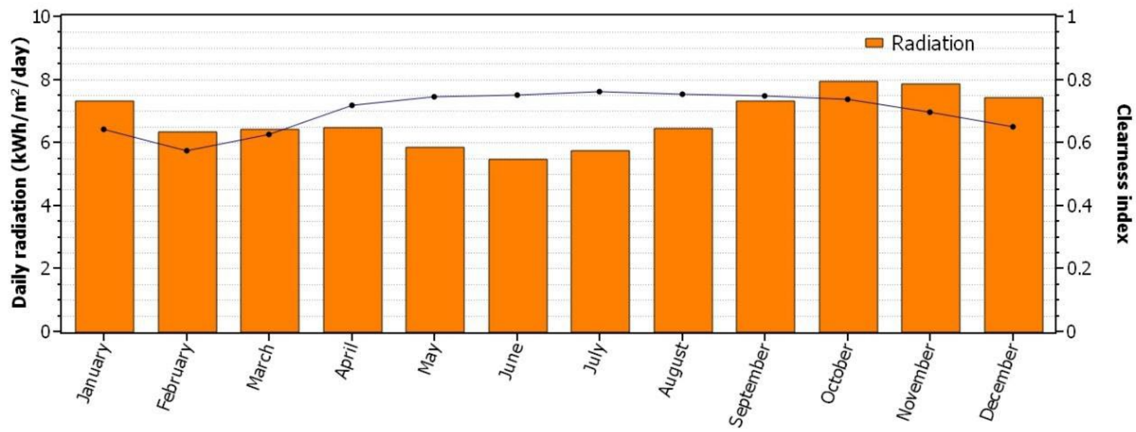


**Figure 3** Monthly solar radiation profile and clearness index in the rural community of San Juan de Tarucani

## 2.4. Software tool

The Hybrid Optimization Model for Electric Renewable (HOMER) is a simulation tool used for modeling hybrid systems either connected to or isolated from the grid. HOMER allows to determine the optimal size of the capacities of its components through the optimization of its dimensioning and allows to model the optimal dispatch strategies to cover the demand load. The results of the simulation in HOMER allow to carry out techno-economic, electrical production and environmental analysis.

There are options other than HOMER, as shown in table 2; however, HOMER was elected according to the context and because this case is a hybrid system.

**Table 2** Alternatives to HOMER

| | HOMER | PVsyst | SolarAnywhere | System Advisor Model |
|---|---|---|---|---|
| Focus | Hybrid systems | Solar photovoltaic systems | Solar photovoltaic systems | Solar photovoltaics and thermal systems |
| Complexity | High | Medium | Medium | Medium |
| Climate data | Predefined climate models | From various sources | Accurate and up-to-date | Accurate and up-to-date |

The input data for performing the analysis in HOMER include prices and sizes of components, load profile, meteorological data and other technical characteristics. The HOMER program performs several simulations until an optimal configuration is found, which is achieved with the minimum NPC and COE [24].

To evaluate the effectiveness of the proposed hybrid system, HOMER analyzes important parameters such as NPC, COE and RF [25]. This allows evaluating the optimal design of the system in the selected region to meet the desired load.

### 2.5. Hybrid system design

In this study, a HES consists of four components such as the photovoltaic system, converter, batteries and diesel generator to satisfy the load demand of the San Juan de Tarucani community. Figure 4 shows the design of the photovoltaic hybrid system in the community of San Juan de Tarucani. In this HES structure, the loads are connected to the AC bus, and a photovoltaic power system and an energy storage unit are connected to the DC bus. A bi-directional power converter links the DC bus to the AC bus for power transfer. In this structure, batteries store excess electricity when the photovoltaic system cannot serve the required load, while the diesel generator serves as a backup power source when the photovoltaic system and storage batteries fail to meet the load [26].

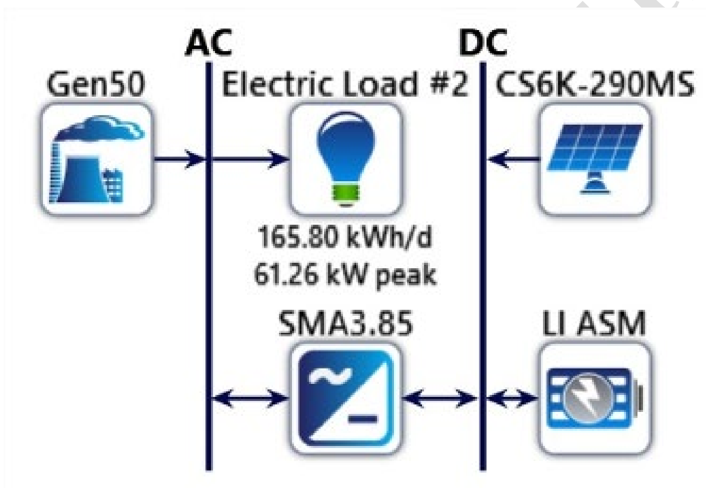


**Figure 4** Configuration of proposed renewable energy integrated off-grid system

### 2.6. Technical and economic inputs

The technical and economic parameters of the hybrid system are considered input parameters that allow the simulation and optimization of the system required by the HOMER program. Table 3 describes in the row and column the technical-economic parameters and the system components (Solar PV, Battery, Inverter, Diesel generator), respectively. The techno-economic parameters describe the type of technology and manufacturer, as well as its operating life for each component of the HES. Also, the capital cost of the system, replacement cost and the Operation and Maintenance (O&M) cost for each of its system components are detailed. Monocrystalline systems have better efficiency even though the price of polycrystalline systems is lower. As it is an isolated system, generation is prioritized.

**Table 3** Techno-economic details of the input parameters for all HES components

| Technical and economic input parameters | Solar PV | Battery | Inverter | Diesel generator |
|---|---|---|---|---|
| **Type of technology and manufacture** | Monocrystalline- Flat plate (Canadian Solar) | Li-ion (Generic) | Sunny boy (SMA America) | Small genset (Generic) |
| **Operational lifetime** | 25 years | n/a | 15 years | 15 000 hrs |
| **Size considered** | 0-90 kW | 0-40 | 0-110 kW | 0-70 kW |
| **Capital cost** | $ 645/kW | $ 600/bty | $ 348.4/kW | $ 306/kW |
| **Replacement Cost** | $ 484/kW | $ 450/bty | $ 261/kW | $ 230/kW |
| **O&M** | $ 13/kW | $ 12/kW | $ 7/Kw | $ 6/kW |
| **Technical parameters** | Nominal max. Power: 290 W | Nominal voltage: 3.7 v | input (DC) | Min. load ratio: 25 % |
| | Opt. Operating voltage (Vmp): 32.1 v | Nominal capacity: 1.02 kWh | Max. usable DC power: 4,200 W | Fuel resource: Diesel |
| | Opt. Operating current (Isc): 9.05 A | Max. capacity: 276 Ah | Max. DC voltage: 600 v | Diesel fuel Price: $ 0.961/L |
| | Temperature coefficient on power: -0.390 %/ºC | Initial state of charge: 100 % | Output (AC) | Lower heating value: 43.2 Mj/kg |
| | Nominal operating cell temperature: 45 ºC | Min. state of charge: 20 % | AC nominal power: 3,330-3,840 W | Density: 820 kg/m3 |
| | Efficiency at standard test conditions: 17.72 % | degradation limit: 30 % | AC voltage range: 211-264 v | Carbon content: 88 % |
| | | String Size: 4 (14.8 v) | Efficiency (97.2 %) | sulfur content (0.4 %) |

## 3. Results

### 3.1. Optimization results

The simulations and optimization carried out by the HOMER program to find the most feasible combination of the hybrid system in cost and technical parameters are based on the restrictions and input data that have been given. The optimization model performed by HOMER is presented in tables that specify the initial capital cost, NPC, COE, type of dispatch, renewable energy fraction, and capacity shortage of the HES.

To optimize system size, HRES designed with optimization variables were simulated by varying the number of batteries and the photovoltaic and diesel generator capacity for off-grid systems. The search space and optimizer are options offered by the HOMER program to perform the optimization of the system, which consist of searching for the optimal capacity or quantity of each component of the system.

The search space is used to vary the capacity of the diesel generator between 0, 10 and 30 kW. These settings were given to find the best optimization results.

After simulating and optimizing the NPC, COE, and RF values for the proposed hybrid energy system (PV/Diesel/Batteries) at the selected location, the results are presented in Table 3. This table details the capacities of the components, economic costs, renewable fraction, fuel costs, as well as different system configurations. Our design, under the PV/Diesel/Battery configuration, shows a minimum NPC of $309,701.30, a COE of $0.396/kWh, and a RF of 93.45%, making it more economically viable and less polluting for the community of San Juan de Tarucani, compared to the optimized PV/Battery system, which has higher NPC and COE values, but no pollutant emissions. The optimization also provided information on the sizing of the PV/Diesel/Battery system configuration, resulting in a 53.8 kW photovoltaic system, a 30-kW diesel generator, and 228 battery groups, using an optimal dispatch strategy based on Load Following (LF).

**Table 4** Categorized and overall optimization results

**OPTIMIZATION RESULTS**

Detailed simulation results — ✓ Categorized — Overall

| Architecture | | | | | | | | | Cost | | | | System | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | DG | BAT | INV | CS6K-290MS (kW) | GEN50 (kW) | Li ASM | SMA3.8 | DISPATCH | COE (US$) | NPC (US$) | Operating Cost (US$/yr) | Initial Capital (US$) | Renewable Fraction (%) | Total Fuel (L/yr) |
| ✓ | ✓ | ✓ | ✓ | 53.79 | 30.00 | 228.00 | 36.13 | LF | 0.396 | 309,701.30 | 9,007.43 | 193,257.60 | 93.45 | 1,471.11 |
| ✓ | | ✓ | ✓ | 129.00 | | 234.00 | 65.00 | LF | 0.453 | 354,040.00 | 8,348.00 | 246,117.00 | 100.00 | 0 |

Detailed simulation results — Categorized — ✓ Overall

| Architecture | | | | | | | | | Cost | | | | System | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PV | DG | BAT | INV | CS6K-290MS (kW) | GEN50 (kW) | Li ASM | SMA3.8 | DISPATCH | COE (US$) | NPC (US$) | Operating Cost (US$/yr) | Initial Capital (US$) | Renewable Fraction (%) | Total Fuel (L/yr) |
| ✓ | ✓ | ✓ | ✓ | 53.79 | 30.00 | 228.00 | 36.13 | LF | 0.40 | 309,701.30 | 9,007.43 | 193,257.60 | 93.45 | 1,471.11 |
| ✓ | ✓ | ✓ | ✓ | 53.26 | 30.00 | 234.00 | 34.46 | LF | 0.40 | 309,841.10 | 8,810.98 | 195,937.00 | 92.87 | 1,560.35 |
| ✓ | ✓ | ✓ | ✓ | 54.92 | 30.00 | 228.00 | 35.62 | LF | 0.40 | 309,855.10 | 8,976.56 | 193,810.40 | 93.32 | 1,488.80 |
| ✓ | ✓ | ✓ | ✓ | 50.23 | 30.00 | 240.00 | 34.15 | LF | 0.40 | 309,982.50 | 8,702.67 | 197,478.50 | 92.70 | 1,588.61 |
| ✓ | ✓ | ✓ | ✓ | 52.11 | 30.00 | 234.00 | 35.56 | LF | 0.40 | 310,035.20 | 8,853.74 | 195,578.40 | 93.27 | 1,497.60 |
| ✓ | ✓ | ✓ | ✓ | 53.81 | 30.00 | 228.00 | 36.80 | LF | 0.40 | 310,113.10 | 9,019.63 | 193,511.60 | 93.67 | 1,436.09 |
| ✓ | ✓ | ✓ | ✓ | 58.46 | 30.00 | 228.00 | 33.12 | LF | 0.40 | 310,413.80 | 8,910.05 | 195,229.00 | 92.23 | 1,668.76 |
| ✓ | ✓ | ✓ | ✓ | 55.35 | 30.00 | 228.00 | 36.35 | LF | 0.40 | 310,470.90 | 8,982.90 | 194,344.30 | 93.59 | 1,444.17 |
| ✓ | ✓ | ✓ | ✓ | 54.65 | 30.00 | 228.00 | 37.13 | LF | 0.40 | 310,635.70 | 9,009.28 | 194,168.00 | 93.80 | 1,411.84 |
| ✓ | ✓ | ✓ | ✓ | 51.85 | 30.00 | 234.00 | 36.82 | LF | 0.40 | 310,677.40 | 8,882.52 | 195,848.50 | 93.71 | 1,426.77 |
| ✓ | ✓ | ✓ | ✓ | 53.31 | 30.00 | 234.00 | 35.97 | LF | 0.40 | 310,795.20 | 8,841.77 | 196,493.10 | 93.47 | 1,461.90 |
| ✓ | ✓ | ✓ | ✓ | 54.33 | 30.00 | 234.00 | 35.44 | LF | 0.40 | 310,906.40 | 8,813.49 | 196,969.80 | 93.31 | 1,485.20 |

### 3.2. Power generated by the photovoltaic, diesel generator and battery discharge status

Figure 5 shows the output power of the system (Photovoltaic, Diesel, Battery) in kW throughout the year, including the battery discharge simulated in the HOMER program. The output power of the PV presents a higher generation compared to the diesel generator, which reaches values of around 50 kW, as shown in Figure 5, and the battery discharge power to cover the demand load has values that reach 40 kW in every month. In addition, the diesel generator to support the system (PV, battery) has higher participation when the demand load increases and is not covered by the system.

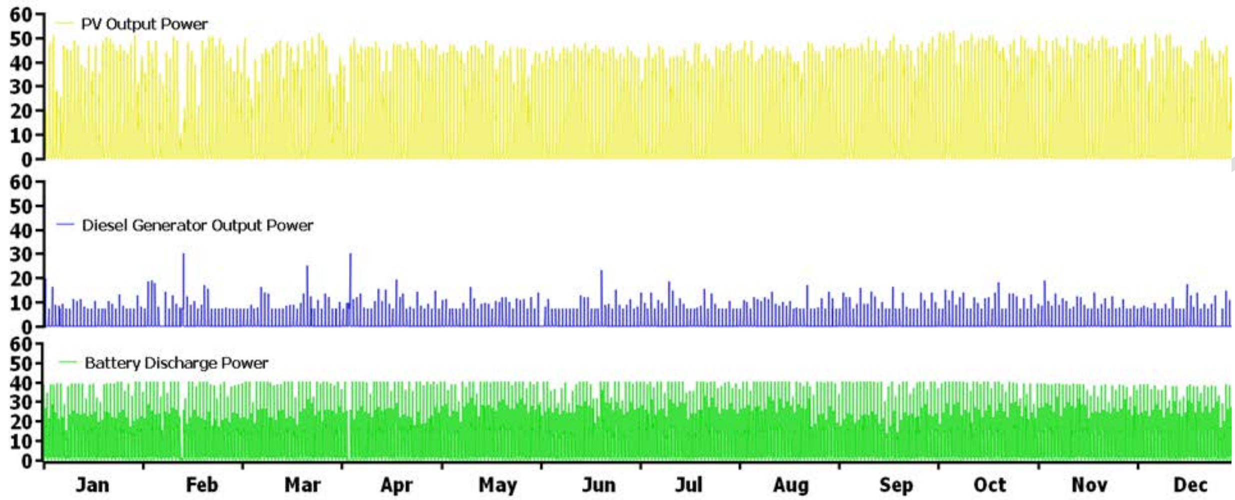


**Figure 5** The output power of the PV system, diesel generator and the discharge power of the battery in kW units throughout the year

### 3.3. Techno-economic analysis

The economic analysis of the proposed HES using PV, Diesel, and Battery was simulated with a nominal discount rate of 8% and a project lifetime of 25 years in the HOMER program. The results of the optimization of the hybrid system are summarized in **Figure 7**, where the total capital cost of the system, operation and maintenance (O&M) cost, and replacement cost are $ 193,257.61, $ 52,261.90, and $ 51,261.34, respectively. Additionally, the cost of fuel amounts to $ 18,276.10, while the salvage value is -$ 5,355.64.

**Figure 6** shows the total costs of the hybrid system and shows that the capital cost of the lithium-ion battery is higher than the other components. This value represents 70.8 % of the total capital cost of the system. Also, the lowest capital cost is the diesel generator.

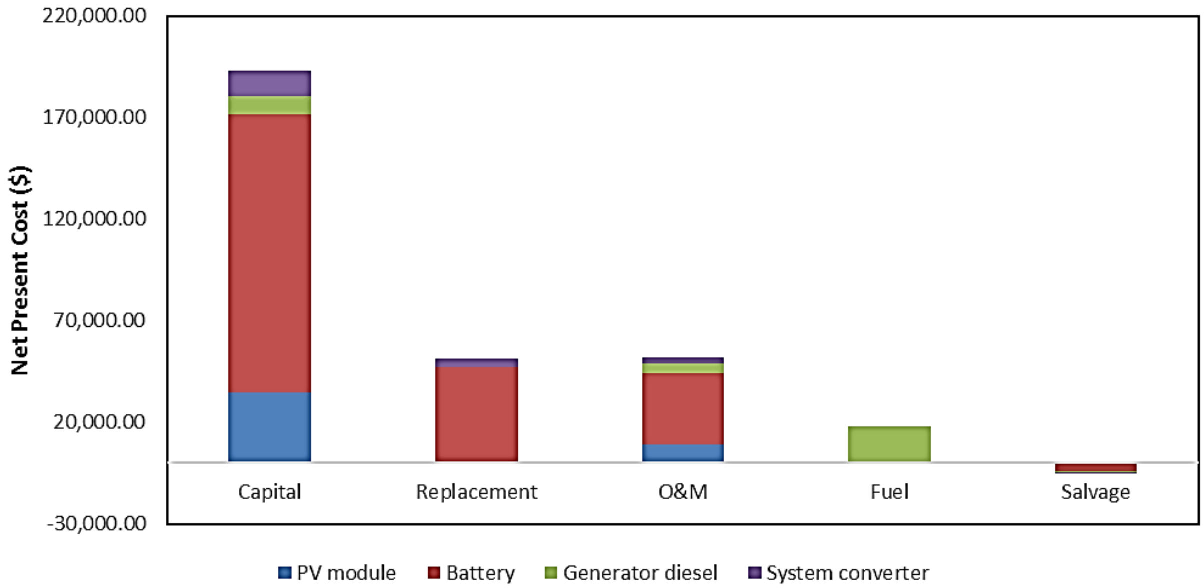


**Figure 6** Cash flow from the optimal configuration of the HES

### 3.4. Electricity production

**Figure 7** shows the monthly electrical output of the proposed system. The photovoltaic solar system generates more electrical energy, especially in the months of September, August and December, where there is a large amount of solar energy. The months with the lowest generation of solar energy are the months of February and March, possibly due to precipitation or cloudy days at the site. **Table 4** shows the average monthly electricity production of the system. The optimal results of the system indicate that the photovoltaic generator and the diesel generator produce 116,378 kWh/year and 3,960 kWh/year, which represent 96.7 % and 3.29 %, respectively. The system results in a total electricity production of 120,337 kWh/yr (100 %), with a total of 49,001 kWh /yr (40.1 %) of excess electricity, 42.4 kWh/yr (0.0701 %) of electricity not satisfied and 59 kWh/yr (0.0975 %) of capacity shortage.

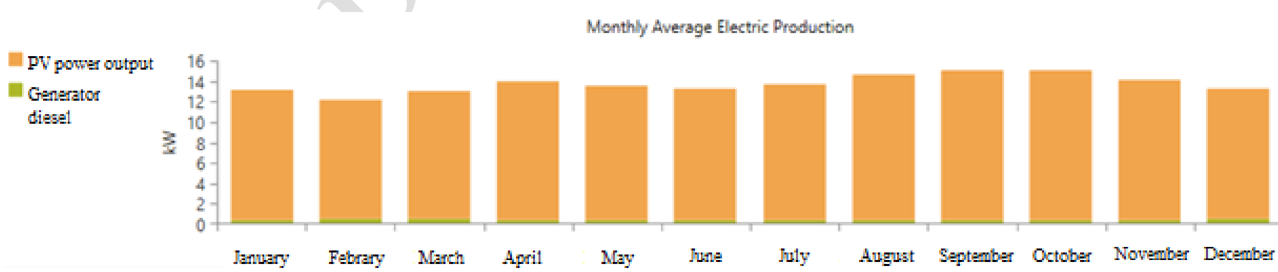


**Figure 7** Monthly electricity production from the photovoltaic and generator optimal system

**Table 5** Annual electric energy production, consumption, excess electricity and renewable fraction

| Component | Production (kWh/yr) | Fraction Renewable (%) | Load | Consumption (kWh/yr) | Fraction Renewable (%) |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Photovoltaic | 116 378 | 96.7 | AC Primary load | 60 474 | 100 |
| Generator diesel | 3 960 | 3.29 | DC Primary load | 0 | 0 |
| Total | 120 337 | 100 | Total | 60 474 | 100 |
| **Quantity** | **kWh/yr** | **Fraction (%)** | **Quantity** | **Fraction (%)** | |
| Excess electricity | 49 001 | 40.7 | Renew. Fraction | 93.5 | |
| Unmet electric load | 42.4 | 0.0701 | Max. Renew. Penetration | 78 820 | |
| Capacity shortage | 59 | 0.0975 | | | |

### 3.5. Operation strategy of the HES

**Figure 8** details the operation strategy of the LF type and the state of charge of the battery obtained from the optimization result. From 17:00 to 5:00, the output power of the photovoltaic shows a decrease due to the sunset at the site, so the battery begins to discharge the energy stored in the day to cover the demand load until the next day. Between 05:00 and 6:50, there is a large increase in demand load not being covered by the battery power discharge, requiring the support of the diesel generator to cover that excess. After this time, there is a decrease in the battery power discharge caused by its minimum State of Charge (SOC) and an increase in the PV output power, covering the load and reducing the participation of the diesel generator. From 9:00 to 16:00, the demand load is minimal, so the excess PV output power is stored in the battery.

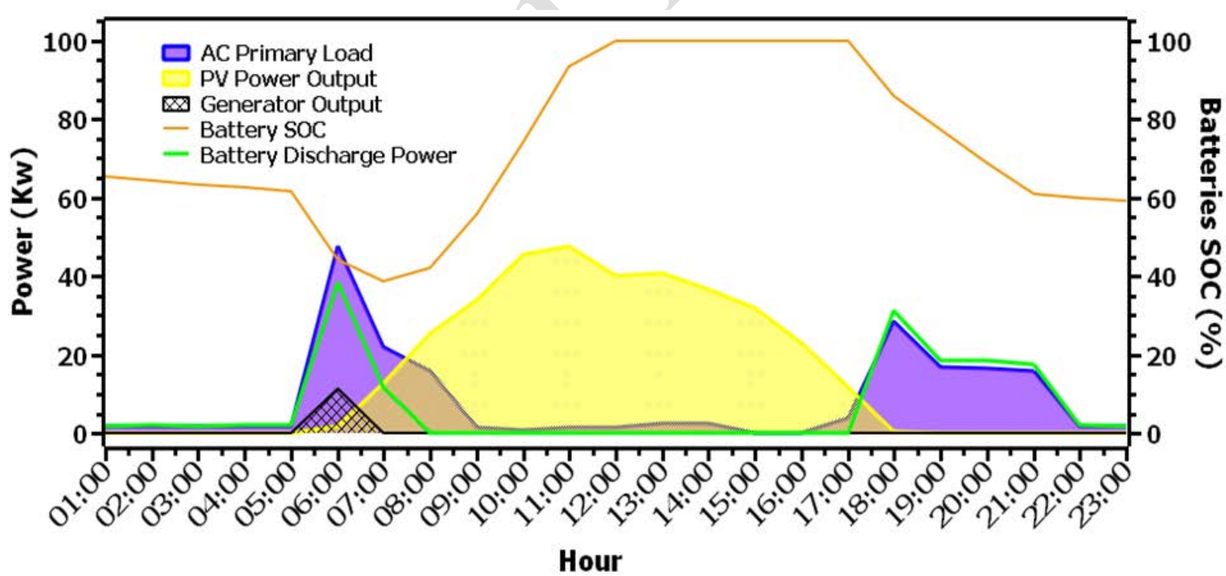


**Figure 8** Energy flow of the photovoltaic battery and diesel system to meet the demand

### 3.6. Environment impact

Greenhouse gas (GHG) emissions are assessed for the PV/diesel/battery and PV/battery system configurations. This system has the highest emission of greenhouse gases with a total of 3,908.23

kg/years. Instead, for the PV/battery configurations, they have zero GHG emissions because the system works with 100 % renewable energy. Regarding the renewable fraction in the configuration of both systems, the first configuration presents a fraction of 93.5 % less than the second, which presents 100 %. These configurations in the proven zero-emission hybrid systems are the greenest. **Table 6** presents the GHG emissions produced by the two configurations simulated by HOMER.

**Table 6** Greenhouse gas emission by the hybrid energy system

| | GHG emission | |
|---|---|---|
| Pollutants (kg/yr) | PV/Diesel/Battery | PV/Battery |
| Amount of Carbon dioxide ($CO_2$) emission | 3,851 | 0 |
| Amount of Carbon monoxide (CO) emission | 24 | 0 |
| Amount of Unburned hydrocarbons emission | 1.06 | 0 |
| Amount of Particulate matter emission | 0.14 | 0 |
| Amount of Sulfur dioxide ($SO_2$) emission | 9.43 | 0 |
| Amount of Nitrogen oxides ($NO_2$) emission | 22.6 | 0 |
| Total | 3,908.23 | 0 |

## 4. Discussion

The combination of components in a hybrid system for different scenarios results in a more reliable PV/battery/diesel configuration, both in terms of techno-economic and environmental analysis. Additionally, it provides a more stable energy generation and supply to the demand load compared to the PV/battery configuration, making it the most suitable solution for electrifying areas without access to the power grid. This is explained by the authors [27,28], who indicate that hybrid systems under the combination PV/battery/diesel provide better reliability and reduce the cost of energy to the system. This type of system provides a solution to the uncertainty problem and reduces the use of the diesel generator.

The optimal dispatch strategy of the PV/battery/diesel hybrid system minimizes the use of the diesel generator, thus reducing fuel consumption. Comparing our results with other studies, the proposed hybrid system exhibits a lower Net Present Cost (NPC) and higher Renewable Fraction (RF) compared to similar configurations reported in the literature. This demonstrates the environmental and economic advantages of the proposed configuration in rural electrification contexts. This is achieved through the LF mode, which allows for system control by considering the following aspects, as noted by Park *et al.* [29]: (i) maximizing the use of solar energy, (ii) minimizing fuel consumption, (iii) optimizing the battery bank size, and (iv) ensuring that the diesel generator provides constant power to support the system.

The design and simulation of the hourly operation of a hybrid photovoltaic system, consisting of batteries and diesel generator, to meet the energy demand of the community of Tarucani has been successful using the HOMER program. The program through its optimization algorithm found optimal values of the sizing of the generation system, determining two possible systems that can meet the electricity demand of the site analyzed. System A consists of photovoltaic panels (PV), inverter, diesel generator, and batteries, it has optimal values of 53.79 kW capacity for the PV system, a 36.13 kW inverter, and 228 batteries, which are sufficient to meet the site's energy demand. This system has a NPC of $ 309,701.30 over its lifetime, a COE of $ 0.396/kWh, greenhouse gas emissions of 3,908.234 kg/year, and a renewable fraction (RF) of 93.5 %. On the other hand, System B, which consists of PV, inverter and batteries, reached optimal values of 129 kW for the PV array, a 65-kW inverter, and 234 batteries. The costs associated with this system are an NPC of $354,040.00, a COE of $0.453/kWh, and a RF of 100%. Although this system is more expensive than System A, primarily due to the higher number of batteries, it is also more environmentally friendly as it operates with 100 % renewable energy.

Comparing our results with those of other authors, the hybrid Wind/PV/Diesel/Batteries system proposed by Rehman *et al.* [14] reports a COE of $ 0.45/kWh, slightly higher than our System A, and an NPC of $ 359,465, which is also higher. However, its RF is lower (84 %), and its emissions (24,466 kg/year) are significantly higher. This suggests that our System A is more efficient in terms of emissions and RF, despite including a diesel generator. Regarding the PV/Diesel/Wind/Batteries system by Rasool *et al.* [16], although it achieves a much lower COE ($ 0.292/kWh) and an NPC of $ 238,330, its RF of 85.7 % is lower than our System A. Additionally, this system covers a smaller daily demand (173.12 kWh), which may partly explain the difference in costs and efficiency. The study by Pazmiño *et al.* [17] presents a COE of $ 0.359/kWh and a significantly lower NPC ($ 152,502) for a PV/Diesel/Batteries system. However, no information is provided about the renewable fraction, and the difference in costs could be due to the system's scale or configuration, making direct comparison difficult. On the other hand, the PV/Diesel/Batteries system proposed by Hidalgo *et al.* [18] shows a COE of $ 0.559/kWh and a very low NPC ($ 102,027), but its RF of only 22.3 % makes it much less environmentally sustainable compared to our System A. Finally, the PV/Batteries system by Rinaldi *et al.* [30] reports a COE of $ 0.542/kWh, which is higher than that of our systems, and an NPC of $ 216,657, which is considerably lower. Its RF of 86.8 % is comparable to our System A but is still lower than that of System B in our study, which achieves a 100 % renewable fraction.

It is worth mentioning the work of Arevalo-Cordero et al. [31] where, seeking to reduce Diesel consumption for off-grid installations, they propose a hybrid model integrating photovoltaic systems, batteries, hydrokinetic energy and wind turbines with Diesel equipment, managing to optimize the system for substantial fuel savings and thus reducing $CO_2$ emissions.

Therefore, the systems A and B developed in our study provide an advantageous balance between cost and sustainability. System A is especially competitive regarding both cost and renewable energy fraction, while System B, despite its higher expense, achieves 100 % renewable energy, making it a more environmentally friendly option. Although some studies propose more economical alternatives, they often result in a lower percentage of renewable energy or higher emissions. This underscores the competitiveness and sustainability of our systems compared to those suggested by other authors.

## 5. Conclusions

The paper presents the modeling and optimization of HES used for electrifying the community of San Juan de Tarucani, Arequipa, Peru. Various factors were considered for the development of the system operational generation of energy strategy. These include the energy demand estimation, source allocation, emissions generated by the system, and comparison of economic aspects. They also included climatic variations, which cause problems in meeting the energy demands when using a single renewable energy source. Moreover, the combination of a HES has been evaluated through HOMER program.

In this research, the design, simulation, optimization of the capacities and its dispatch strategy in hybrid energy systems were carried out with the configuration of solar photovoltaic, diesel generator and an energy storage system (battery). The optimization analysis was performed to determine the best capabilities of the hybrid system in terms of NPC, COE and RF.

The results indicate that the HES, incorporating photovoltaic solar energy, diesel generator, and battery storage, successfully meets the community's energy demand year-round, achieving 100% load coverage and an excess energy of 40.1 %, allowing the community to increase its energy consumption. Among all the combinations of the components, the optimization result turned out to be more viable to the proposed HES. The results obtained were minimum values of NPC ($ 309,701.00) and COE ($ 0.40), and a high value of RF of 93.45%, indicating that the system is environmentally viable. The participation of the diesel generator to support the system is minimal, which allows a reduction in investment and O&M costs. After analyzing the obtained results, this proposed model provides the best compromise solution for the community.

## Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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## Author contributions

Responsible for drafting the manuscript, conducting the technical data analysis, and performing the simulations using the program: J. J. Peñalva-Sánchez; provided a thorough technical and theoretical review of the article: José C. Álvarez; Contributed to the development of the methodology, reviewed the scientific literature, and conducted the overall review of the manuscript J. E. Luyo-Kuong and J. Peralta-Jaramillo.

## Data availability statement

The authors state that the data supporting the findings of this study are available in the article [and/or] in the supplementary materials

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