Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 5, October 2025, pp. 3327~3340
ISSN: 2302-9285, DOI: 10.11591/eei.v14i5.9589

Feasibility study of solar-diesel generation hybrid power systems: a case study of rural electrification in Papua, Indonesia

Marthen Liga[1], Aris Sampe[1], Johni Jonatan Numberi[2]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Cenderawasih, Jayapura, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Cenderawasih, Jayapura, Indonesia

Article Info

Article history:

Received Nov 21, 2024
Revised Jul 23, 2025
Accepted Aug 8, 2025

Keywords:

Feasibility
Hybrid power system
Renewable energy
Rural electrification
Technical-economic analysis

ABSTRACT

This study presents a contextually tailored off-grid hybrid energy system consisting of solar photovoltaic (PV), diesel generator (DG), and battery storage, designed for the remote mountains village of Jifak in Papua, Indonesia. The objective is to evaluate the technical, economic, environmental, and social feasibility of electrification in underserved regions. A comprehensive feasibility analysis was conducted using HOMER software, incorporating realistic communal load profiles, National Aeronautics and Space Administration (NASA) climate data, and field-based social assessments. The optimized system achieved a net present cost (NPC) of $10.43 million, a levelized cost of energy (LCOE) of $0.5095/kWh, and annual emissions of 7,965 kg CO_2. Sensitivity analysis was performed on fuel cost, discount rate, and inflation rate to assess system robustness. Beyond the technical metrics, the study assessed the socio-economic impacts of electrification, revealing improvements in lighting quality, education, productivity, income generation, and environmental awareness. The findings provide a replicable model and decision-making framework for policymakers and practitioners aiming to deploy low-carbon, sustainable electrification strategies in similarly remote regions.

Corresponding Author:

Marthen Liga
Department of Electrical Engineering, Universitas Cenderawasih
Kamwolker Kampus Baru Waena-Papua, Jayapura, Indonesia
Email: marthen_liga@ftuncen.ac.id

1. INTRODUCTION

Electrical energy increases proportionally to population expansion, which drives home electrical appliance consumption and industrial growth in emerging countries. Greater access to dependable energy services drives sustainable local economic growth. However, developing countries, where more than people lack electricity, face this energy shortage. These populations are mostly in remote, powerless rural areas. Thus, grid extension electricity supply systems are often uneconomical and unfeasible. The International Energy Agency (IEA) reported in 2022 that fossil fuels have provided 80% of global energy over the decades. In 2030, natural gas, oil, and coal will peak [1]. Many environmental and health issues result from fossil fuel use. Additionally, these resources are going to run out soon. Consequently, a substitute electricity generation is essential.

Renewable energy is leading the energy transition due to environmental concerns, the decline of conventional energy sources (coal, oil, and natural gas), and their rising costs [2]. Renewable energy sources, which use clean, unlimited natural energy, can meet today's energy needs. Renewable energy sources are sustainable and have fewer environmental impacts than fossil fuels. These benefits are increasing interest in renewable energy [3]. According to the IEA data for 2022, global clean energy investment rose 40% from

2020. IEA energy outlook study recommends distributed approaches as the most cost-effective option for lighting over fifty percent of the nation's 77 million population until 2030. [1]. Diversifying electricity supply will ensure electricity security for developing countries, especially rural areas. Worldwide, renewable energy systems are seen as the best option for rural electrification and a major contributor to sustainable energy infrastructure. Most places have clean, environmentally friendly RES.

In 2022, Indonesia's renewable energy supply reached 30 million TOE, constituting 12.3% of the total primary energy supply [4]. Nonetheless, the status of renewable energy accomplishments remains inferior to the forecasts established by the National Energy General Plan, as illustrated in Figure 1.

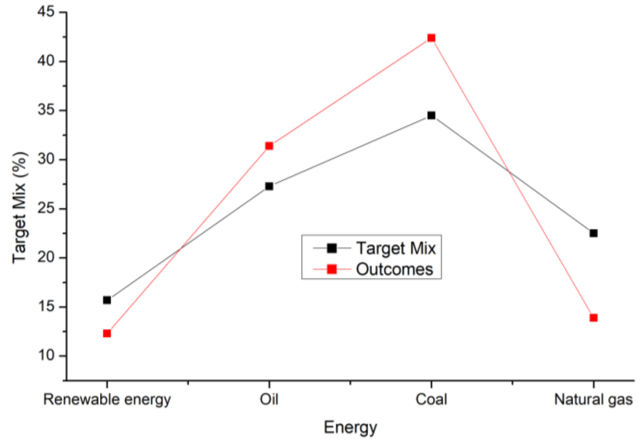


Figure 1. Primary energy mix in 2022

Indonesia possesses substantial potential for renewable and new energy. Figure 2 illustrates the updated data on renewable energy potential in 2021. By 2022, we have only harnessed 0.3%, or 12.6 GW, of the total 3.687 GW of renewable energy potential for power generation. The limited utilization of renewable energy for electricity generation is due to the comparatively high cost of new renewable energy-based power plants. Consequently, it is challenging to calculate the efficiency of fossil fuel power plants, particularly those utilizing coal. Furthermore, investing in renewable energy requires significant capital due to the lack of support from the domestic industry for new renewable energy components and the difficulty in securing low-interest funding or loans.

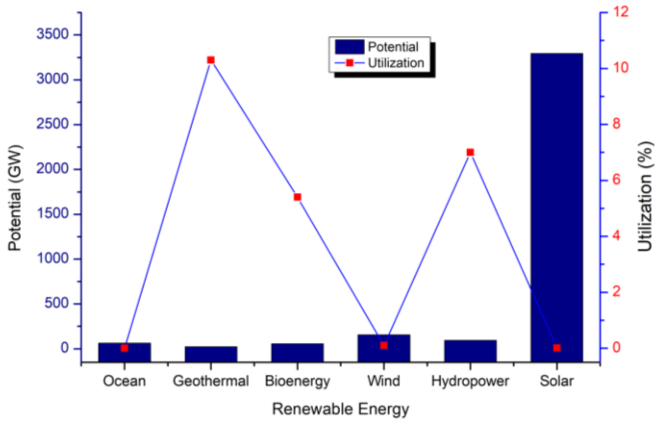


Figure 2. Potential and utilization of renewable energy in 2022

Renewable energy sources are unstable and cannot generate energy regularly. Hybrid power sources are being used to solve this problem. Hybrid energy systems generate energy from multiple sources [5]–[7]. These systems collaborate to produce energy more efficiently. Other energy sources can compensate for one's inactivity in these systems. The environmental impact of hybrid systems is also significant. Facilities for hybrid generation based on renewable energy are necessary to lower CO_2 emissions. Research indicates that fish farming and campus energy needs can effectively utilize alternative power-based hybrid systems. Hybrid technologies can reliably meet agricultural, commercial, and other energy needs outside suburban zones and since the power lines does not accessible. Generating electricity near consumption centers reduces transmission line losses. Energy efficiency and economic losses will improve with fewer losses. In earthquake-prone areas, producing electrical energy from local resources is essential to meet post-disaster energy demand.

– Literature review

Addressing rural communities' energy needs with one renewable energy source is insufficient and sometimes uneconomical. Renewable energy is stochastic. Solar photovoltaic (PV) output is highly dependent on insolation, which changes daily. A variety of operational, economic, social, policy, and regulatory issues. Integrating numerous renewable energy sources into a hybrid power system is better than utilizing one or an expansion of the national grid to improve rural electricity supply. Two complementary energy generation and storage systems make up a renewable energy system. Subsequently may use only renewable energy, non-renewable energy, or both. It boosts power supply efficiency and sustainability. Hybrid power systems are now widely used in remote rural areas for efficient and reliable off-grid power. The system can also be enhanced with storage units. Thus, when energy generation is high, the rest is stored for later use. Storage units raise system costs and cause losses.

Many authors have studied renewable energy technologies and their solutions worldwide. A 248 kWh/day hybrid system with a peak load of 44.41 kW is both economically and technically feasible. This setup yields 60% RF, $0.28/kWh cost of energy (COE), and $612,280 net present cost (NPC). The decrease in carbon dioxide emissions when utilizing batteries compared to diesel generators (DG) is 59.6% and 40.5%, respectively [8]. Power from the hybrid system costs 5.51 PKR/kWh, resulting in a savings of 4.84 PKR/kWh relative to the utility price of 10.35 PKR/kWh. The payback period is 9.5 years, a reduction from the initial projection of 25 years by Shahzad *et al.* [9]. Halabi *et al.* [10] concluded that hybrid systems in the region can improve the economy with the creation of new jobs. Kundankar and Katti [11] conducted a hybrid hydro-PV system can serve a load of 58.9% with a composition of PV 47.8%, micro-hydro 11.1% and the rest is stored in the battery. The battery can store energy safely for 5.26 hours with a capacity of 100 kWh. Analysis of levelized cost of energy (LCOE), NPC, and CO_2 between PV-diesel-battery configurations resulted in NPC of $158,206 and COE of $0.895/kW more economical and environmentally friendly when compared to DG alone [12], [13]. PV/wind/DG/battery with 90% renewable energy penetration, COE $0.213, NPC $187 [14]. Research was conducted in rural areas off-grid as well as on-grid. The on-grid system [15]–[17] is carried out in areas that have a national distribution network system or in areas where there is no distribution network but it is economically profitable to do an interconnection system rather than an isolated system, on the other hand, the off-grid hybrid system [18]–[20] is carried out on communal loads and does not have access to the national distribution network. Research of hybrid systems in Indonesia have been undertaken, encompassing PV-diesel, PV-diesel-wind, and hydro-diesel configurations. This is attributable to various factors, notably the prevalence of conventional energy sources in the electrical systems of rural and island regions. The second factor is that the potential for solar and wind energy sources is extensive and widespread across all regions [5], [13], [21]–[23].

The paper presents an original hybrid energy model that is context-specific and adapted to the distinct socio-environmental conditions of Papua, Indonesia, integrating multi-scenario technical-economic-environmental analysis with community-level social effect evaluation. In comparison with previous research, this study introduces a novel, comprehensive feasibility framework that employs realistic communal load data and field-based social insights. This model is replicable and can be used to elucidate underserved mountainous regions in a similar manner.

– Aim of the study

Most of the authors discussed above conducted research on various renewable energy sources and hybrid system topologies that can meet the energy needs of various study areas. Very few have conducted research on hybrid DG and solar PV using the study area of Papua, Indonesia. In other words, the various hybrid system setups studied differ in terms of parameters such as load demand, application, study site, vegetation, and climate data. Using Jifak village as a case study, this paper examines the technical and economic viability of an off-grid PV/DG/battery hybrid system for rural electricity in Papua, the hybrid system reduces costs, meets load demand, improves rural socio-economic welfare, and quality of life without harming the environment.

Organization of the paper: section 1 covers the study's progress, previous research, as well as goals. Section 2 covers the research region, system design, and energy analysis. The findings and evaluation are in section 3. Section 4 offers suggestions and findings.

2. METHOD

2.1. System design

Figure 3 presents a comprehensive flowchart outlining the updated research methodology for designing a hybrid solar PV–diesel–battery system aimed at rural electrification in Jifak, Papua. The process begins with defining the project objective—delivering electricity access to the rural community. This is followed by data collection, which includes daily and hourly load profiles, and solar radiation and temperature data sourced from National Aeronautics and Space Administration (NASA). After gathering the necessary data, the system configuration step specifies the components to be modeled, such as PV panels, DG, batteries, and inverters. These configurations are then inputted into HOMER Pro software, where both load and resource data, along with component specifications and cost parameters, are entered.

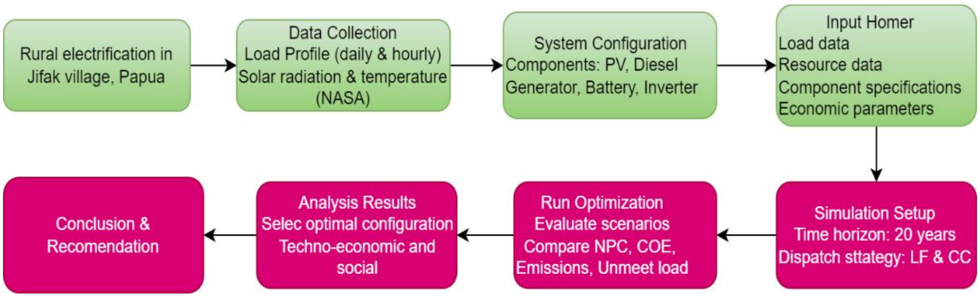


Figure 3. Methodology for hybrid solar-diesel-battery system

The flowchart's second section covers modeling and analysis. Load following (LF) and cycle charging dispatch techniques are used in the simulation to determine a 20-year project time horizon. Next, the optimization procedure assesses numerous scenarios using NPC, COE, emissions, and unmeet load. After optimization, analysis findings choose the best configuration based on techno-economic and social impact. The final recommendation suggests the region's most cost-effective and sustainable hybrid energy system.

The model depicted in Figure 4 comprises a solar energy source, a DG, a battery, and an inverter. The evaluation of multiple situations is conducted via HOMER software. The proposed energy management model effectively and economically satisfies the energy requirements of the load. To fulfill load demands, an inverter converts PV system-generated DC energy into AC. These systems store some of their energy in batteries and use inverters to convert it back to AC for AC loads. DG supply AC power straight to AC loads. When constructing a hybrid system, a feasibility study must be conducted effectively.

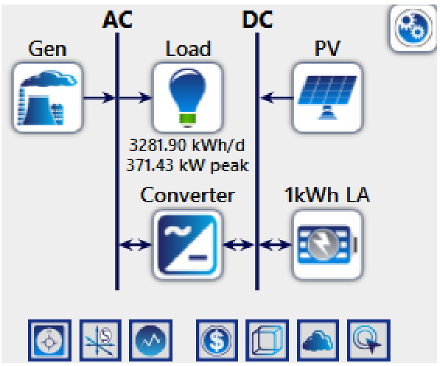


Figure 4. Proposed hybrid system design in HOMER

HOMER program simulates the best economic, environmental, and technical system. The program offers a user-friendly interface for designing and optimizing grid-connected or standalone hybrid energy systems. It can concurrently simulate loads and energy units, including PV panels, wind turbines, fuel cells, hydroelectric power plants, biomass energy sources, regenerative generators, battery storage systems, and gas tanks [7], [24], [25].

HOMER classifies various configurations based on their order of suitability. The software not only performs complex calculations of the above-mentioned systems, but also performs a thorough analysis of environmental impacts such as greenhouse gas emissions. The literature review showed that HOMER software is often used in research on hybrid renewable energy systems because it can model, improve, and study complicated energy systems that use both renewable and traditional energy sources. Choosing the right sizes for components, examining costs like NPC and LCOE, and testing how changes in fuel prices, renewable resources, and energy demand affect the system make it easier to study if the system will work well [20], [26], [27]. HOMER helps designers make cost-effective and efficient hybrid energy solutions by checking both connected and standalone systems, looking at resource changes every hour, and studying key reliability factors like power shortages and the risk of outages. Its widespread use in academics and industry makes it essential for renewable energy planning and microgrid feasibility assessments.

2.2. Load profile

In this study, a renewable energy-based microgrid with DG is modeled to meet the electrical energy needs in rural areas. Jifak village in Suru-Suru district, Papua which is located at the location point -4.77772, 138.5205 is the research location [28], [29]. Figure 5 presents the load profile that will supply 100 household units. Other facilities are the village hall, school and house of prayer each totaling 1 unit. Jifak village has an average energy of 3281.9 kWh/day with 136.75 kW of power. The maximum power is 371.43 kW, accompanied at an operating ratio of 0.37.

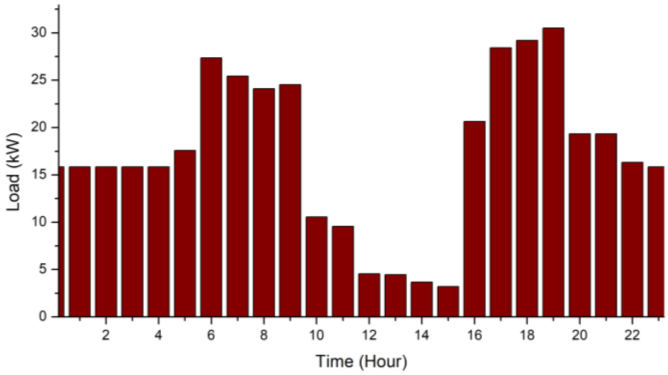


Figure 5. Load profile

2.3. Wheather condition

Two meteorological characteristics serve as input variables for HOMER program to analyze the optimal design of microgrid systems utilizing PV electricity at the study sites. The solar radiation and temperature profiles at each site are different for each location in Indonesia. Hence, the findings in the present research may be taken to develop a PV/DG hybrid system to fulfill the supply of electrical power on remote islands. The parameters used are solar radiation and brightness index as shown in Figure 5 while the temperature is shown in Figure 6.

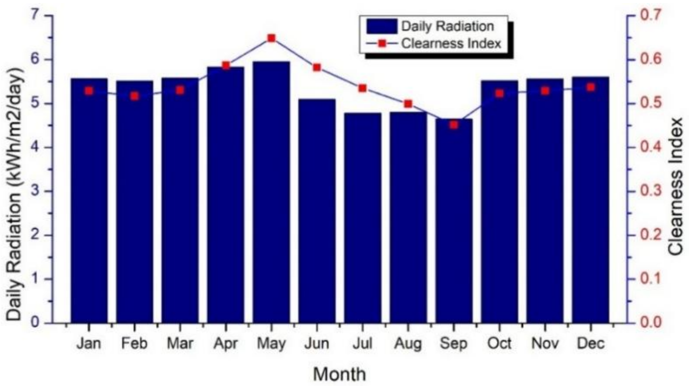


Figure 6. Radiation and clearness index

Figure 6 illustrates the correlation between solar energy and the brightness rating provided by the NASA (https://power.larc.nasa.gov/data-access-viewer/) from 2013 to 2023 [30]. The average solar radiation throughout the year is 4.68 kWh/m^2/day. The highest radiation is in the months of January and February while the lowest is in July. The trend of the clearness index curve is similar to that of the radiation with the highest in January at 0.492 and the lowest in August.

Figure 7 represents the monthly variation of daily temperature. From January to May, the daily temperatures hover between 22.79 °C and 21.67 °C, showing a stable and relatively consistent temperature pattern.

A notable dip is observed in June, where the temperature decreases to approximately 21.4 °C, which is the lowest point on the chart. The months of July and August continue to reflect lower temperatures, around 20.21 °C, indicating a possible cooler season during mid-year. Starting from September, temperatures begin to rise again, with October and November showing a significant increase, peaking around 21.59 °C in November, which is the highest recorded temperature. December shows a slight decline from the November peak but remains relatively high compared to the mid-year values. This cyclical pattern suggests a seasonal variation, with cooler temperatures around mid-year and warmer temperatures at the beginning and end of the year, which could be relevant for renewable energy generation potential, especially for systems dependent on temperature fluctuations.

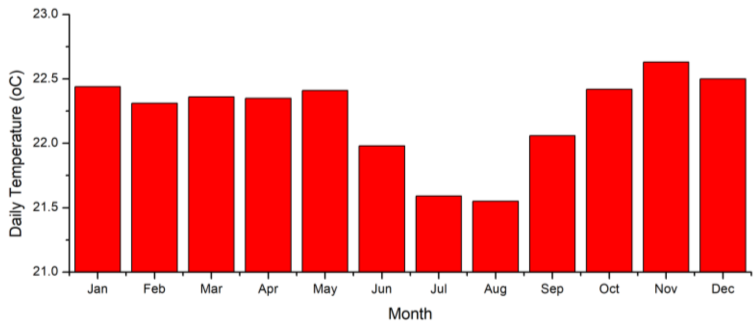


Figure 7. Temperature

2.4. Mathematical system component models

2.4.1. Diesel generator

The output of a DG (P_{DG}) is contingent upon fuel consumption and efficiency, with the fuel consumption rate (F) determined for electricity generation. Both variables can be determined using (1) and (2):

$$P_{DG} = \frac{m_{fuel}\ x\ \eta_{DG}\ x\ LHV}{t} \tag{1}$$

$$F = aC_{DG} + bP_{DG} \tag{2}$$

where m_{fuel} is fuel mass consumed (kg), η_{DG} is efficiency of the DG, LHV is lower heating value of the fuel (kJ/kg), and t is time (hours). The product's data sheet gives fuel curve slopes a and b as 0.246 L/kWh and 0.08145 L/kWh, as well. C_{DG} is the DG capacity and P_{DG} its electrical power. The utilization of fuel (F) is none whenever the DG gets idle, but this formula applies when it is running. DG replacement costs depend on operating hours.

The NPC of a DG (NPC_{DG}) is determined by its initial expense (C_{DG}), fuel price (F), maintenance and operational rate (C_{OM-DG}), and the cost of substitution (C_{R-DG}) as expressed in (3)–(5):

$$NPC_{DG} = C_{DG} + C_{OM-DG} + C_{R-DG} + F \tag{3}$$

$$C_{DG} = \eta_{DG}\ x\ P_{DG} \tag{4}$$

$$C_{OM-DG} = t_{run}\ x\ \sum_{i=1}^{n}\left(\frac{1+\beta}{1+r}\right)^{i} \tag{4}$$

2.4.2. Solar photovoltaic

Solar panel power production is determined by employing (6):

$$P_{PV} = Y_{PV} f_{PV}\left(\frac{G_T}{G_{T,STC}}\right)\left[1 + \alpha_p(T_C - T_{C,STC})\right] \tag{6}$$

where Y_{PV} is the output power of the solar panel under (STC) conditions (kW), α_p is the power temperature coefficient $(^{\%}/_{°C})$, f_{PV} is the capacity reduction factor (%), $G_{T,STC}$ refers to the incident radiation under STC standards $(^{1\ kW}/_{m^2})$, G_T is the direct solar radiation on the solar panel $(^{1\ kW}/_{m^2})$, T_C is the temperature of the solar cell (°C), and $T_{C,STC}$ is the temperature of the solar cell under STC standards (25 °C). G is the solar radiation $(^{1\ kW}/_{m^2})$. The calculation of solar cell temperature is influenced by ambient temperature and solar radiation shown in (4) [31].

2.4.3. Battery system

For off-grid PV-diesel-battery hybrid energy systems, lead-acid batteries have been used. Parameters that are often considered include lifespan, efficiency, and total cost. The specifications of battery modules with hybrid energy systems depend on the depth of discharge, temperature, and life of the battery. The battery state of charge (SOC) may be calculated by applying (7) and (8):

$$SOC_{(t+1)} = SOC(t)[1 - \sigma(t)] + \left[\frac{I_b(t)\Delta t\eta_C(t)}{C_B}\right] \quad (7)$$

$$SOC_{(t+1)} = SOC(t)[1 - \sigma(t)] + \left[\frac{I_b(t)\Delta t\eta_D(t)}{C_B}\right] \quad (8)$$

where SOC is the state of charge, σ(t) is the periodic discharge rate per hour, I_b is the battery current, C_B is the battery nominal capacity (A hours), $t\eta_C$ is the charging effectiveness, and η_D is the discharge effectiveness. Battery systems store and release energy based on SOC. The stored energy E_{bat} in a battery is modeled by (9):

$$E_{bat} = E_{rated}\ x\ SOC \quad (9)$$

where E_{rated} is rated battery capacity (Wh or kWh) and SOC is state of charge, typically between 0 (empty) and 1 (full).

Table 1 shows the economics of the hybrid energy system's DG, solar PV panels, battery system, and energy converter. DG require initial investment, replacement, and continuing maintenance. It has a lifespan and needs a minimum load to run properly, depending on fuel price and capacity. The PV system's installation, replacement, and annual maintenance costs indicate its low running costs and long-term viability. Lead-acid batteries require one-time purchase, replacement, and annual maintenance, and their economic performance depends on how often they are charged and discharged. The converter, which converts AC/DC power between system components, is the most expensive per unit capacity due to its technical role in system efficiency and stability, with significant capital and maintenance expenses. Optimizing system configuration and assessing feasibility with HOMER Pro requires component cost and performance assumptions.

Table 1. Parameter economy of components [13]

Parameter		Value	Unit
Diesel generator	Capital cost	1,500	$/kW
	Replacement cost	750	$/kW
	O&M cost	0.081	$/kW/hour
	Lifetime	150,000	Hour
	Minimum load rasio	25	%
	Diesel price	1.162	$/L
	Capacity factor	70-89	%
PV	Capital cost	1,320	$/kW
	Replacement cost	1,000	$/kW
	O&M	40	$/kW/yr
Battery	Capital cost	300	$
	Replacement cost	200	$
	O&M	40	$/kW/yr
Converter	Capital cost	3,000	$/kW
	Replacement cost	2,500	$/kW
	O&M	800	$/kW/yr
Economic parameters	Inflation rate	3	%
	Discount rate	4.88	%

3. RESULTS AND DISCUSSION

3.1. Optimization result

The HOMER modeling is a powerful tool for hybrid system feasibility studies. The simulation includes system optimization and sensitivity analysis to provide significant insight into the feasibility of various configurations. The optimization findings are presented from two unique perspectives: a comprehensive overview featuring all feasible hybrid systems, sorted by COE and increasing NPC values. The NPC defines the price derived by deducting the current fair value of all costs associated with the setup and operation of the system parts during the project's lifespan from the prospective value of all revenues generated throughout the duration of the project. COE is the average cost of producing 1 kWh of useful energy in the system (excluding losses) over its lifetime.

In the simulation process, HOMER estimates the cost and at the same time determines the feasibility of hybrid systems throughout the year with a list of system configurations and their capacities sorted by the lowest

COE and NPC. In this study, among many configured energy systems, six different scenarios were evaluated to find the optimized system configuration both technically and economically as presented in Table 2.

Table 2. Simulation results summary of different scenarious

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
DG capacity (kW)	410	410	410	-
PV capacity (kW)	-	5.48	-	2,113
Inverter capacity (kW)	-	1.38	0.431	344
Number of battery	-	9	22	5,321
Capital costs ($)	165,000	629,060	622,892	5.42 M
Replacement costs ($)	236,331	240,606	240,959	3.41 M
Operating costs ($)	4.9 M	4.99 M	4.99 M	9.78 M
Fuel costs ($)	4.7 M	4.76 M	4.77 M	-
Excess energy (kWh/yr)	0	1,589	0	1,263,790
Unmeet load (kWh/yr)	0	0	0	105
Fuel consumption (L)	348,639	347,422	348,639	-
Specific fuel consumption (L/kWh)	0.291	0.291	0.291	-
Carbon dioxide (kg/yr)	7,992	7,964	7,992	-

3.2. Cost analysis

In addition to carefully considering costs and rewards, the economic analysis also looks carefully at the overall financial picture of the system. A careful in-depth analysis shows that there are two main parts: replacement cost and O&M price. Resource selection during system design determines installation cost. The operating cost depends on whatever source produces how much when. All these difficulties complicate hybrid system design. Comparative investigations were done across all system configurations with uniform boundary values. Choosing the best energy system involves minimizing NPC, COE, renewable energy percentage, capacity shortages, surplus power, and fuel use. A thorough examination of these factors yields an ideal energy system with lower NPC and COE, higher renewable energy fraction, fewer capacity shortages, less surplus power, and lower fuel use. In quest of sustainable and efficient hybrid energy solutions, this thorough technique ensures informed decision-making.

Figure 8 showed the relationship between the COE and the NPC across four different scenarios. In scenarios 1 to 3, the COE remains relatively constant, hovering around $0.50, while the NPC also remains relatively stable, with minor variations at around $10.5 million. This suggests that the costs associated with these scenarios are relatively optimized, with a balance between energy cost and total system cost. However, in scenario 4, there is a significant increase in both COE and NPC. The COE jumps to around $0.86, while the NPC rises sharply to approximately $17.77 million. This drastic change indicates that scenario 4 involve additional factors and higher operational costs that drastically increase the overall economic burden of the system. It could represent a less efficient scenario, possibly due to higher fuel dependence, increased operational complexity, or expensive storage components within the hybrid energy system. Analyzing these patterns helps identify optimal configurations for minimizing costs in renewable energy systems.

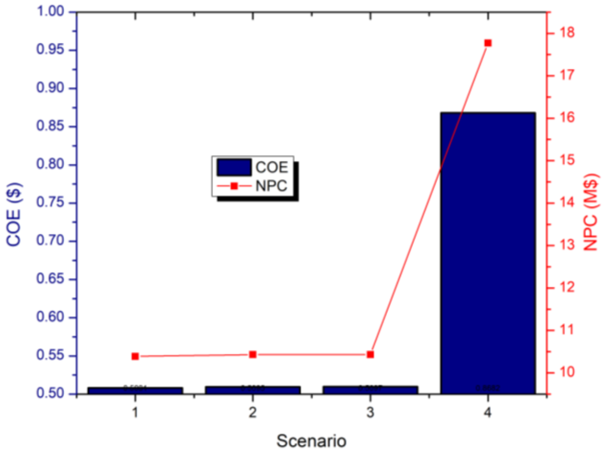
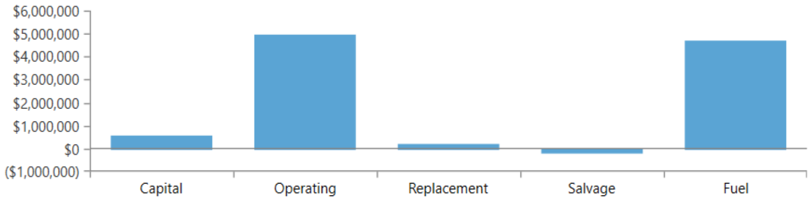


Figure 8. Comparison between COE and NPC

Figure 9 reveals areas for cost savings and optimization in the hybrid DG-PV system. The generator's fuel and O&M costs are high. This illustrates the financial costs associated with diesel dependence. Solar is cost-effective over time because the PV system has lower costs in most categories, especially fuel (zero) and O&M. Increasing PV capacity or energy storage could reduce generator usage and fuel and O&M costs. Total cost includes capital, O&M, fuel, replacement, and salvage. Due to high O&M and fuel costs, the generator accounts for most of the "system" total of $10,427,436.42. Diesel fuel costs $4,749,125.92, demonstrating operational dependence on a non-renewable resource.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Autosize Genset	$615,000.00	$236,331.91	$4,970,559.36	$4,749,125.92	($188,121.94)	$10,382,895.23
Generic 1kWh Lead Acid	$2,700.00	$1,543.50	$6,150.85	$0.00	$0.00	$10,394.35
Generic flat plate PV	$7,233.36	$0.00	$3,745.06	$0.00	($805.87)	$10,172.54
System Converter	$4,126.82	$2,730.78	$18,802.53	$0.00	($1,685.83)	$23,974.30
System	$629,060.18	$240,606.19	$4,999,257.79	$4,749,125.92	($190,613.65)	$10,427,436.42

Figure 9. NPC of each component of scenario 2

Figure 10 illustrates that all simulated renewable energy system scenarios exhibit a negative return on investment (ROI) in comparison to the pure diesel system (DG only), which serves as a reference with an ROI of 0%. The DG/battery scenario exhibits an ROI of -23.5%, signifying the most substantial economic detriment attributed to the elevated expenses of batteries in the absence of renewable energy support. The DG/PV/battery and PV/battery scenarios exhibit negative ROIs of -10.8% and -10.1%, respectively, indicating that the savings from reduced fuel use are insufficient to offset the initial investment expenses. This hybrid system is currently not economically viable under existing simulation settings; nonetheless, it possesses potential for enhancement via technical optimization and policy assistance.

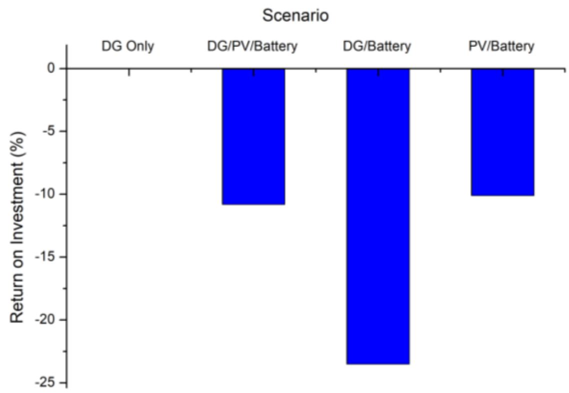


Figure 10. Comparison of ROI in various scenarios

Figure 11 shows the sensitivity of NPC and COE to changes in diesel fuel price, showing that both metrics increase as fuel price rises from $0.80/L to $1.00/L. This indicates that the economic performance of the hybrid energy system worsens with higher fuel costs, primarily due to the increased operational expenses of the DG. The NPC, representing the total lifetime cost, and COE, representing the average cost of electricity production, both show sharp increases initially and begin to stabilize slightly at higher fuel prices. This trend highlights the importance of integrating more alternative power sources, like solar PV and batteries, to reduce dependency on diesel and improve the system's long-term economic sustainability.

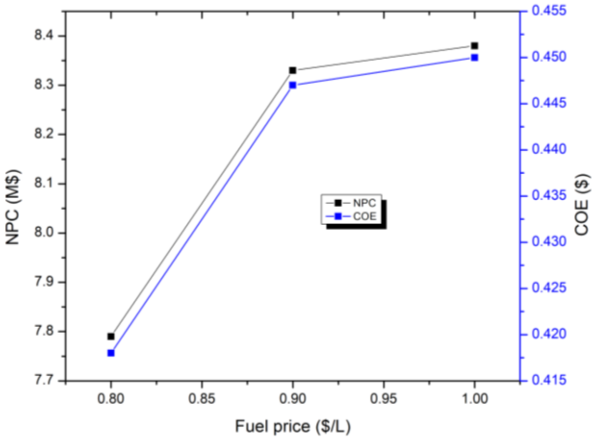


Figure 11. The relationship between fuel prices and NPC and COE

Figure 12 presents the sensitivity of the NPC and COE to variations in discount rate and inflation rate in a hybrid renewable energy system simulated by HOMER model. The left chart illustrates that increasing the discount rate leads to a decrease in NPC due to heavier discounting of future costs, while COE slightly increases, reflecting the higher relative weight of upfront capital costs. In contrast, the right chart shows that as the inflation rate rises, NPC increases because future costs such as fuel and maintenance become more expensive, while COE decreases slightly due to the effect of inflation on discounted energy production costs [32]. These trends highlight the importance of accurately estimating financial parameters, as they significantly affect the perceived economic viability of hybrid energy systems.

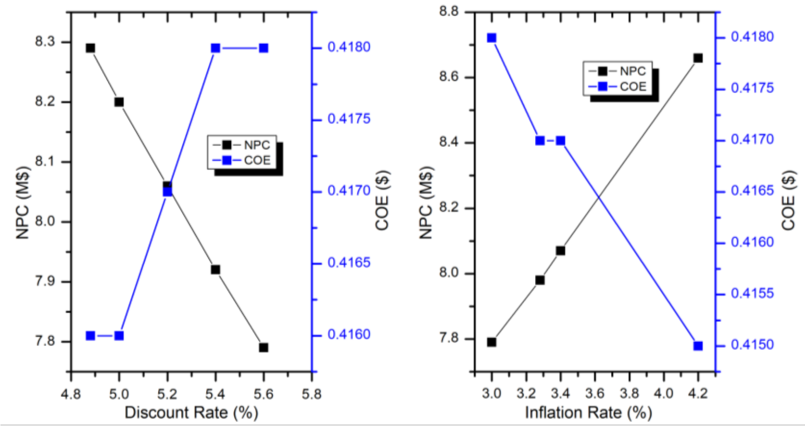


Figure 12. The relationship between discount rate, inflation rate with NPC and COE

3.3. Electrical production

Figure 13 illustrates the annual energy generation by DG and PV systems under various scenarios. Scenario 1 shows high DG production with low PV input, indicating high DG reliance. In scenario 2, DG production remains high, similar to scenario 1, but PV contribution is at its highest, showing an increased role for PV, though still much lower than DG. In scenario 3, DG production drops significantly and PV contribution drops to near zero, suggesting limited power production from both sources. The graph shows that all scenarios rely heavily on DG, especially scenarios 1 and 2. PV contributes significantly only in scenario 2, while scenario 3 shows minimal power from both sources, likely due to energy requirements or source configurations.

Figure 14 shows how important the DG is in this hybrid system, as PV alone cannot meet demand. HOMER software can optimize such a system by adjusting PV capacity or load requirements to improve energy mix, cost-efficiency, and environmental impact. This system appears to rely on the DG to meet energy demand, likely due to low PV production throughout the year. This could mean the PV capacity is low, the solar potential is low, or the system prioritizes the generator for stable, continuous energy supply.

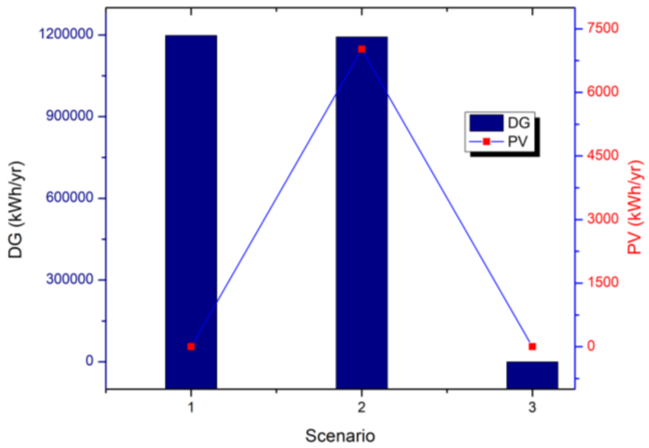


Figure 13. Annual energy generation

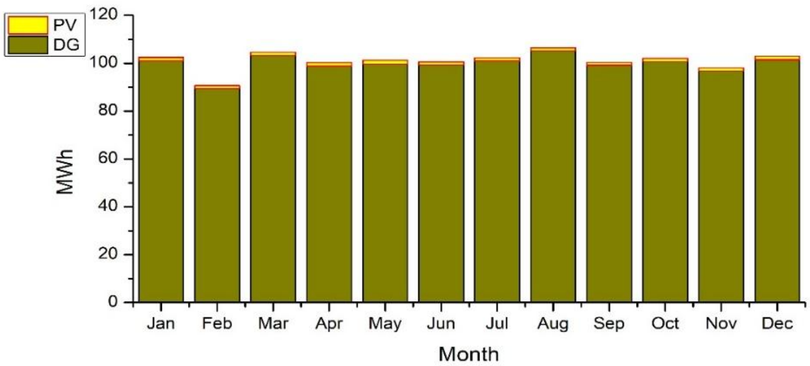


Figure 14. Montlhy electric production of scenario 2 (DG-PV)

3.4. Social benefit

Today's society relies on electricity, which may transform an individual's and community's socioeconomic existence. This research reports the social advantages of regional electrification based on field visits, expert opinion, personal assessment, and literature review. It is observed that electricity is an essential need for the local people to improve their socio-economic status. Access to electricity infrastructure is an essential step in modern activities and plays a significant role in improving the socio-economic conditions of communities. In addition, electricity services enable community members, especially women and children, to make the best use of their time in household activities and education, thereby increasing household income.

Green power sources, including solar, wind, and hydro, are generally more labor-intensive than fossil fuel or nuclear power generation units. These technologies require workers for manufacturing, installation, operation, and maintenance, often at a higher rate than the highly automated processes found in traditional energy sectors. Consequently, renewable energy creates significantly more jobs per unit of energy produced. For example, studies have shown that solar PV employs about twice as many workers as coal plants per megawatt of energy generated [33]. These jobs cover a range of roles, from research and development in new renewable technologies to positions in local project installations and maintenance. Furthermore, as the renewable energy sector expands, it generates regional jobs, benefiting local communities and reducing dependency on centralized, nonrenewable plants [34].

Rural electricity helps combat destruction of forests since rural residents cook with wood and natural wastes. Lamp and biomass cooking smoke is harmful. Without clean drinking water, the community suffers serious health issues. Electricity is necessary for drinking water and irrigation pumping systems. Research shows that after getting electricity, users can work after sunset, earning extra money from various activities and improving their social life and status. Electricity brings radio and TV to the locals, keeping them informed and entertained. Hybrid power systems may improve rural communities' living standards, economic activity, women's empowerment, security, employment, and sustainable development.

4. CONCLUSION

This study examines the possible use of hybrid systems for electrifying rural villages by modeling an efficient hybrid energy system with optimal cost assessment and emission management of hazardous substances. The present research examined four distinct scenarios of hybrid systems, selecting ideal configurations from minimized energy costs, reduced greenhouse gas emissions, and their respective pros and drawbacks. The research also investigated the significant results of various configurations in terms of NPC, COE, emission, capacity of renewable energy and renewable energy penetration. Using the developed HOMER model, the paper conducted a technical, economic, and environmental analysis. The results showed an annual emissions level of 7,965 kg, a LCOE of $0.5095, and a NPC of $10.43 million. The effects of electrification on lighting, education, social structure, the environment, and household income are examined in this paper. Electricity has improved the economic status of villagers, according to the research, because it automates daily tasks, provides better lighting, and powers productive activities.

This study supports the use of an off-grid PV/DG/battery hybrid system as a sustainable solution for electricity of remote are in Jifak, Papua, offering an alternative to grid extension. It demonstrates the techno-economic viability of similar structures in the region, considering Papua’s high solar energy potential. However, the study's use of generalized communal loads and the absence of sensitivity analysis for key variables, such as diesel price, limit its optimization accuracy.

To ensure successful adoption, the study recommends targeted policy and operational measures, including financial incentives, technical regulations, capacity building, and the integration of local resources like micro-hydro or biomass. Improvements in storage technology and community-based ownership models are also highlighted to enhance sustainability. Future research should explore the long-term viability of rural electrification by considering institutional, socio-cultural, and economic factors, especially the community’s ability and willingness to manage operation and maintenance costs.

ACKNOWLEDGMENTS

The authors wish to convey our deepest appreciation to Universitas Cenderawasih for providing academic and technical support throughout this research. Special thanks are extended to the local government and community of Jifak Village, Papua, for their cooperation and valuable insights during the field study.

FUNDING INFORMATION

The authors would like to express their gratitude to the Faculty of Engineering, Cenderawasih University, for the funding provided under contract number 7730.DBA.004.B525119, year 2025.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Marthen Liga	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	
Aris Sampe		✓				✓		✓		✓	✓	✓		
Johni Jonatan Numberi			✓	✓	✓		✓			✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

REFERENCES

[1] International Energy Agency, "World Energy Outlook 2023 | Enhanced Reader," 2023. https://www.iea.org/news/the-energy-world-is-set-to-change-significantly-by-2030-based-on-today-s-policy-settings-alone. (Date accessed: Oct. 10, 2024).

[2] S. Bertrand, "Climate, Environmental, and Health Impacts of Fossil Fuels (2021)," *Environmental and Energy Study Institute*, 2021. https://www.eesi.org/papers/view/fact-sheet-climate-environmental-and-health-impacts-of-fossil-fuels-2021. (Date accessed: Nov. 06, 2024).

[3] W. Strielkowski, L. Civín. E. Tarkhanova, M. Tvaronavičienė, and Y. Petrenko, "Renewable Energy in the Sustainable Development of Electrical," *Energies*, vol. 14, pp. 1–24, 2021, doi: 10.3390/en14248240.

[4] S. G. The National Energy Council, "Secretariate General the National Energy Council Indonesia Energy Outlook 2023 Secretariate General the National Energy Council," 2023.

[5] W. Kang *et al.*, "Community microgrid planning in Lombok Island: an Indonesian case study," *Front. Energy Res.*, vol. 11, no. July, pp. 1–12, 2023, doi: 10.3389/fenrg.2023.1209875.

[6] O. D. T. Odou, R. Bhandari, and R. Adamou, "Hybrid off-grid renewable power system for sustainable rural electrification in Benin," *Renew. Energy*, vol. 145, pp. 1266–1279, 2020, doi: 10.1016/j.renene.2019.06.032.

[7] G. M. Shafiullah *et al.*, "Prospects of Hybrid Renewable Energy-Based Power System: A Case Study, Post Analysis of Chipendeke Micro-Hydro, Zimbabwe," *IEEE Access*, vol. 9, pp. 73433–73452, 2021, doi: 10.1109/ACCESS.2021.3078713.

[8] S. Mandal, B. K. Das, and N. Hoque, "Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh," *J. Clean. Prod.*, vol. 200, pp. 12–27, 2018, doi: 10.1016/j.jclepro.2018.07.257.

[9] M. K. Shahzad, A. Zahid, T. Rashid, M. A. Rehan, M. Ali, and M. Ahmad, "Techno-economic feasibility analysis of a solar-biomass off grid system for the electri fi cation of remote rural areas in Pakistan using HOMER software," *Renew. Energy*, vol. 106, pp. 264–273, 2017, doi: 10.1016/j.renene.2017.01.033.

[10] L. M. Halabi, S. Mekhilef, L. Olatomiwa, and J. Hazelton, "Performance analysis of hybrid PV/diesel/battery system using HOMER: A case study Sabah, Malaysia," *Energy Convers. Manag.*, vol. 144, pp. 322–339, 2017, doi: 10.1016/j.enconman.2017.04.070.

[11] R. R. Kundankar and P. K. Katti, "Hybrid Energy System for Remote and Rural Villages," *2018 Int. Conf. Power Energy, Environ. Intell. Control. PEEIC 2018*, no. 2, pp. 619–622, 2018, doi: 10.1109/PEEIC.2018.8665472.

[12] S. K. A. Shezan, "Optimization and assessment of an off-grid photovoltaic–diesel–battery hybrid sustainable energy system for remote residential applications," *Environ. Prog. Sustain. Energy*, vol. 38, no. 6, 2019, doi: 10.1002/ep.13340.

[13] E. K. Bawan, F. D. Wijaya, H. R. Ali, and J. C. Vasquez, "Techno-Economic Analysis of Hybrid Solar Photovoltaic and Microhydro Systems for Rural Areas of Tambrauw, Indonesia," *Energy Inform. Acad. Conf.*, 2024, pp. 317–335, doi: 10.1007/978-3-031-74741-0_21.

[14] P. H. Kumar, R. R. Gopi, R. Rajarajan, N. B. Vaishali, K. Vasavi, and S. Kumar P, "Prefeasibility techno-economic analysis of hybrid renewable energy system," *e-Prime - Adv. Electr. Eng. Electron. Energy*, vol. 7, p. 100443, 2024, doi: 10.1016/j.prime.2024.100443.

[15] P. Malik, M. Awasthi, and S. Sinha, "A techno-economic investigation of grid integrated hybrid renewable energy systems," *Sustain. Energy Technol. Assessments*, vol. 51, p. 101976, 2022, doi: 10.1016/j.seta.2022.101976.

[16] F. Eze, J. Ogola, R. Kivindu, M. Egbo, and C. Obi, "Technical and economic feasibility assessment of hybrid renewable energy system at Kenyan institutional building: A case study," *Sustain. Energy Technol. Assessments*, vol. 51, p. 101939, 2022, doi: 10.1016/j.seta.2021.101939.

[17] S. A. Adetoro, M. N. Nwohu, and L. Olatomiwa, "Techno-economic Analysis of Hybrid Energy System Connected to an Unreliable Grid: A Case Study of a Rural Community in Nigeria," *Proc. 2022 IEEE Niger. 4th Int. Conf. Disruptive Technol. Sustain. Dev. NIGERCON 2022*, pp. 1–5, 2022, doi: 10.1109/NIGERCON54645.2022.9803128.

[18] J. M. Aberilla, A. Gallego-Schmid, L. Stamford, and A. Azapagic, "Design and environmental sustainability assessment of small-scale off-grid energy systems for remote rural communities," *Appl. Energy*, vol. 258, p. 114004, 2020, doi: 10.1016/j.apenergy.2019.114004.

[19] A. S. Aziz *et al.*, "A new optimization strategy for wind/diesel/battery hybrid energy system," *Energy*, vol. 239, 2022, doi: 10.1016/j.energy.2021.122458.

[20] M. A. Saheli, K. Lari, G. Salehi, and M. T. Azad, "Techno-economic assessment of a hybrid on grid PV-wave system: A case study in Caspian Sea," *Renew. Energy*, vol. 186, pp. 596–608, 2022, doi: 10.1016/j.renene.2021.12.146.

[21] D. D. D. P. Tjahjana *et al.*, "Economic Feasibility of a PV-Wind Hybrid Microgrid System for Off-Grid Electrification in Papua, Indonesia," *Int. J. Des. Nat. Ecodynamics*, vol. 18, no. 4, pp. 811–818, 2023, doi: 10.18280/ijdne.180407.

[22] A. W. Putra, E. Kamandika, S. Rosyadi, A. Purwadi, and Y. Haroen, "Study and design of hybrid off-grid PV-generator power system for administration load and communal load at three regions in Indonesia," *3rd IEEE Conf. Power Eng. Renew. Energy, ICPERE 2016*, pp. 57–62, 2017, doi: 10.1109/ICPERE.2016.7904850.

[23] I. Susanto, W. Sunanda, R. F. Gusa, R. Kurniawan, and Y. Tiandho, "Hybrid of photovoltaic and diesel power plant in Celagen Island," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 463, no. 1, 2020, doi: 10.1088/1755-1315/463/1/012119.

[24] Y. Sawle, S. Jain, S. Babu, A. R. Nair, and B. Khan, "Prefeasibility Economic and Sensitivity Assessment of Hybrid Renewable Energy System," *IEEE Access*, vol. 9, pp. 28260–28271, 2021, doi: 10.1109/ACCESS.2021.3058517.

[25] F. Rashid, M. E. Hoque, M. Aziz, T. N. Sakib, M. T. Islam, and R. M. Robin, "Investigation of optimal hybrid energy systems using available energy sources in a rural area of Bangladesh," *Energies*, vol. 14, no. 18, 2021, doi: 10.3390/en14185794.

[26] J. D. D. Niyonteze, F. Zou, G. N. O. Asemota, S. Bimenyimana, and G. Shyirambere, "Key technology development needs and applicability analysis of renewable energy hybrid technologies in off-grid areas for the Rwanda power sector," *Heliyon*, vol. 6, no. 1, p. e03300, 2020, doi: 10.1016/j.heliyon.2020.e03300.

[27] A. I. Hassane, D. H. Didane, A. M. Tahir, R. M. Mouangue, J. G. Tamba, and J. M. Hauglustaine, “Comparative analysis of hybrid renewable energy systems for off-grid applications in chad,” *Int. J. Renew. Energy Dev.*, vol. 11, no. 1, pp. 49–62, 2022, doi: 10.14710/ijred.2022.39012.
[28] C. B. of S. of A. Regency, “Suru Suru Sub District In Figures 2021.” https://yahukimokab.bps.go.id/id/publication/2021/09/28/4d4740afbfd5480b14b263fb/kecamatan-suru-suru-dalam-angka-2021.html. (Date accessed: Oct. 23, 2024).
[29] D. H. Arthanto, A. I. Malakani, B. G. D. Wicaksono, and A. Purwadi, “Off-Grid PV System Modelling for Communal Load at Jifak Village-Asmat Regency, Papua Province Based on MATLAB/Simulink,” *Proc. 2nd Int. Conf. High Volt. Eng. Power Syst. Towar. Sustain. Reliab. Power Deliv. ICHVEPS 2019*, pp. 322–327, 2019, doi: 10.1109/ICHVEPS47643.2019.9011073.
[30] “NASA Langley Research Center, “POWER Data Access Viewer.” https://power.larc.nasa.gov/data-access-viewer/. (Date accessed: Oct. 10, 2024).
[31] M. Hadwan and A. Alkholidi, “Solar power energy solutions for Yemeni rural villages and desert communities,” *Renew. Sustain. Energy Rev.*, vol. 57, pp. 838–849, 2016, doi: 10.1016/j.rser.2015.12.125.
[32] E. K. Bawan, F. D. Wijaya, H. R. Ali, and J. C. Vasquez, “Comprehensive Analysis and Optimal Design of Hybrid Renewable Energy System for Rural Electrification in West Papua , Indonesia,” pp. 1–26, 2025, doi: 10.1109/ACCESS.2025.3556020.
[33] T. Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, and N. Prabaharan, “A comprehensive study of renewable energy sources: Classifications, challenges and suggestions,” *Energy Strateg. Rev.*, vol. 43, p. 100939, 2022, doi: 10.1016/j.esr.2022.100939.
[34] Y. Lv, “Transitioning to sustainable energy: opportunities, challenges, and the potential of blockchain technology,” *Front. Energy Res.*, vol. 11, pp. 1–20, 2023, doi: 10.3389/fenrg.2023.1258044.

BIOGRAPHIES OF AUTHORS

Marthen Liga is a fulltime faculty member in the Department of Electrical Engineering at Cenderawasih University, specializing in Engineering Economics and Electrical Project Management courses. He obtained a Master's degree in Electrical Engineering from Gadjah Mada University in 2008 and a Doctorate in Electrical Project Management from the Doctoral Program in Economics at Cenderawasih University in 2018. He earned his master's degree from the Jakarta Institute of Technology in 2023. His academic specialization encompasses electrical systems, focusing on sustainable energy, electrical power systems, and electrical project management. He can be contacted at email: marthen_liga@ftuncen.ac.id.

Aris Sampe is a permanent lecturer in the Department of Electrical Engineering, Cenderawasih University, teaching courses on Electrical Power Generation, Direct Current Machines, and Electrical Circuits. He earned his Master's degree in Electrical Engineering from Hasanuddin University in 2012. He earned his professional engineering degree from the Jakarta Institute of Technology in 2023. His academic expertise focuses on electrical systems. He can be contacted at email: aris_sampe@ftuncen.ac.id.

Johni Jonatan Numberi is an Associate Professor (*Lektor Kepala*) in Energy at the Department of Mechanical Engineering, Faculty of Engineering, Universitas Cenderawasih, Jayapura, Papua, Indonesia. He currently serves as Head of the Master’s Program in Renewable Energy Engineering at the Graduate School and Director of the Energy Research Center at Universitas Cenderawasih. He earned his Doctoral degree in Mechanical Engineering (Energy Conversion) from Universitas Indonesia, a Master’s degree and a Professional Engineering certification from Universitas Gadjah Mada, and a Bachelor’s degree in Mechanical Engineering from Universitas Negeri Manado. He also completed a three-year technical internship in metal casting in Japan and a one-year energy sector internship in the Netherlands. His research focuses on renewable energy systems, energy planning, solar PV, wind turbines, micro-hydro, biomass, bioethanol, biodiesel, fuel development, and combustion processes. He has led major research collaborations, including the Papua Regional Energy Plan and Papua Energy Profile, and has published in national (SINTA) and international (Scopus) indexed journals. He has received research funding from the Ministry of Education, Research, and Technology of the Republic of Indonesia. He can be contacted at email: johni_numberi@ftuncen.ac.id.