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Economic Analysis of PV-Generator Hybrid Off-Grid Systems in Underdeveloped Indonesian Regions

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ABSTRACT

The escalating demand for electrical energy in both rural and urban sectors necessitates a reliable and sustainable source, as the availability of traditional fossil fuels diminishes and their contribution to global warming becomes increasingly untenable. This study thus explores an environmentally-friendly solution via the Hybrid Renewable Energy System (HRES), a convergence of multiple renewable energy sources for electricity production. The focus is on an off-grid photovoltaic-wind turbine hybrid system that harnesses solar and wind energy to meet the electrical needs of the scarcely accessible Maluku Province. A feasibility analysis is conducted using the Homer software to evaluate the system's potential. The results reveal that Tual City, with the lowest Net Present Cost (NPC) amounting to Rp. 268,439,300.00 and a Cost of Energy (COE) of Rp. 3,220.56, presents the most promising potential for development. The total electricity generated by this hybrid system is projected to reach 9,457 kWh/year, highlighting its potential as a sustainable solution to the pressing energy needs in remote regions.

1. INTRODUCTION

Indonesia is a maritime country that has many islands. The number of islands in Indonesia is estimated at more than 17,000, consisting of five significant mainland's such as Java, Sumatra, Kalimantan, Sulawesi, and Maluku [1]. Of the five major islands in Indonesia, only Java has been utilized optimally and has abundant human resources. Meanwhile, other large and small islands still need to be optimally utilized and still have many potentials that can be developed [2]. One of them is several islands that are part of a province in Indonesia, namely Maluku. Maluku Province is located in the eastern part of Indonesia with the geographical location at coordinates 80 30' – 20 30' South Latitude, 1250 – 1350 10' East Longitude. This province has a land area of 47,350.42 km^2 with 632 large and small islands [3]. In this area, the intensity of solar radiation is large enough to be used in developing solar energy [4].

Power generation requires a variety of energy sources, with a focus on effectively utilizing new and renewable energy sources. Technical, economic, and environmental security concerns must be the main emphasis of policies on the use of new and renewable energy sources as a source of electrical energy [5]. Therefore, the Indonesian archipelago's electrical issue may be solved using renewable energy as a substitute source of energy [6]. The sun has the same economic viability as conventional power plants, is a renewable energy source, and may serve as a clean energy substitute. It is also an extremely plentiful energy source [7]. Due to its two seasonal cycles and archipelagic geography, Indonesia gets traversed by both the west and east monsoons.

Surprisingly, Indonesia is also in the tropics, which means it has the right climate for producing energy at a rate of up to 112,000 GWp per day and has a significant amount of light intensity [8, 9]. Solar and wind energy sources are renewable energy sources, yet they are characterized by very erratic and unpredictable variations. It is highly intriguing to use photovoltaic (PV) systems with diesel engines to harness solar and monsoon resources. Solar energy is mostly usable in the sweltering summer and winter seasons when the sun is out. In contrast, wind is more prevalent at night and throughout the winter [10-12]. Utilizers of solar and additional energy who have been integrated into one utilizing a hybrid system can complement one another using different daily and seasonal changes [13-15].

The market for residential solar systems may see a decrease in PV costs as average power usage rises as a result of these most recent developments. Knowing how to analyse decisions from a political, economic, and technological standpoint is crucial for educating individuals who support the transformation of society to clean energy [16]. Here, the local energy consumption of the research facility is simulated using the HOMER hybrid energy system modelling program [17]. Sensitivity analysis is considered one of the unique properties One of the distinguishing features of HOMER, which can examine the impacts of several factors, is sensitivity analysis. This capability makes the program perfect for comparing the variables affecting the cost-effectiveness of different turbine generators used in local power systems. The elements influencing the economic system are examined in this research [18].

This research describes the possible use of grid-connected photovoltaic energy systems based on the demand for power in Indonesia. By taking into account load needs, the potential for renewable energy sources, the capacity and make-up of power production systems on various Indonesian islands, this research presents the possible utilization of grid-connected photovoltaic-generator energy systems [2]. This research will be able to solve the aforementioned issues by taking into account crucial elements including load needs, renewable energy potential, and the capacity and makeup of the power generation system. The techno-economic analysis also takes use charges and payback periods into account to calculate the time required to recoup investments [19].

This research uses the feasibility analysis method with HOMER software to analyze and compare the configuration of a PV-generator hybrid system connected to off-grid batteries implemented in several remote areas in Indonesia. This research is expected to compare the potential for developing solar energy into electrical energy in these several areas concerning the lowest Net Present Cost (NPC). This research is expected to serve as a reference for developing renewable energy in rural areas as part of the national electrification efforts in Indonesia.

2. MATERIALS AND METHODS

2.1 Regional selection

The case study was chosen to take place in the Province of Maluku, namely in the districts of Buru, Seram, Tual, Aru Islands, and Ambon City. According to Presidential Regulation Number 63 of 2020 about the Determination of undeveloped Regions for 2020–2024, the province is included in undeveloped regions [20].

Maluku is a province with relatively tricky access in Indonesia, so not all areas in this region have been reached with electricity. It is essential to develop renewable energy here, considering the high potential it holds, especially solar energy. In addition, Maluku has limited access to developing conventional energy due to extreme topography and morphology. Therefore, it is necessary to develop electrical resources using renewable energy [21].

2.2 Model description

The HOMER application simulates the potential of a PV-generator hybrid power plant to calculate COE [18]. The parameters considered include solar and wind energy, profile loads, technical and economic components, and location determination [22]. Figure 1 below is a framework for the HOMER simulation that was carried out.

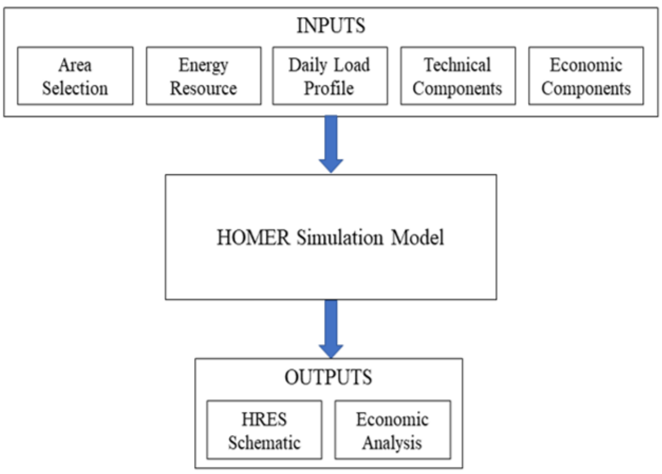

Figure 1. HOMER simulation framework

As seen in Figure 2, this study replicates a grid-connected hybrid PV generator. The system is employed to assess and choose the necessary cost model. The HOMER simulation modelling program is used. A hybrid renewable energy technology (RET) system is configured as part of the HOMER evaluation, which is followed by a techno-economic study. The system's technical qualities and life cycle cost (LCC) are what guide the study, as shown in Table 1 [23]. To maximize system design, installation, and operating costs across the system's lifetime, LCC covers initial capital costs and compares equipment with various restrictions and sensitivities. HOMER creates alternative technologies to address certain demands, enabling simulation [24].

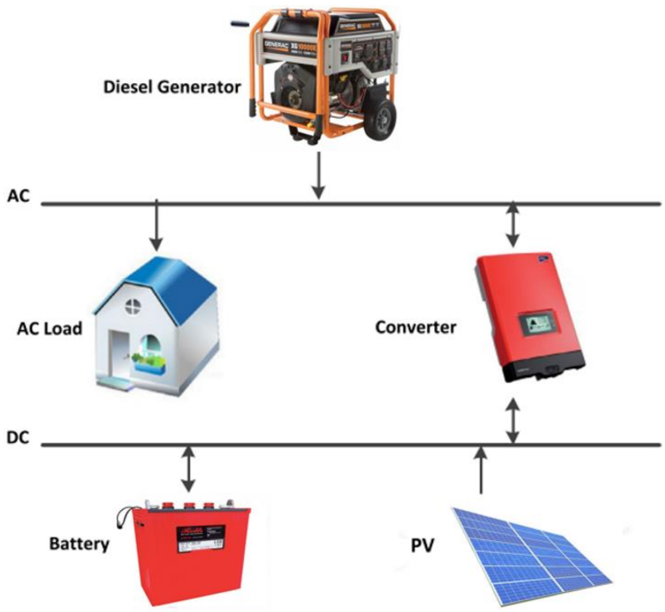

Figure 2. PV-generator hybrid system configuration scheme

HOMER software validates electricity consumption by default for housing needs in Maluku Province. The electricity consumption load in several selected areas has the same value, namely 11.26 kWh/day with a maximum load of 2.09 kW [25]. Figure 3 is an illustration of household electricity consumption in Maluku Province. This province faces challenges in terms of access, and as a result, several areas still need access to electricity. Therefore, it is necessary to develop renewable energy sources here, especially by harnessing the potential of solar energy. The hybrid PV-generator system is one of the solutions that can be implemented in these remote areas. This system consists of several essential components that must be considered to achieve an optimal design and cost. The main components of this off-grid hybrid system include a diesel generator, a solar panel array (PV), and a power converter.

By optimizing the design and considering the costs, the hybrid PV-generator system can become an efficient and sustainable solution to improve electricity access in remote areas of Maluku Province. With the development of renewable energy, it is expected that the communities in the region can enjoy the benefits of more reliable and sustainable electricity.

2.3 Environmental parameters

Ambient temperature, wind speed, and solar radiation in various areas in Maluku Province using Surface Meteorological Data and NASA Solar Energy. Maluku

Province is one of the remote areas where electrical energy is very much needed. This is because conventional electricity cannot fully enter the area. Therefore, it is necessary to develop power plants with renewable energy sources. Several cities in Maluku Province will be selected to be the subject of this research.

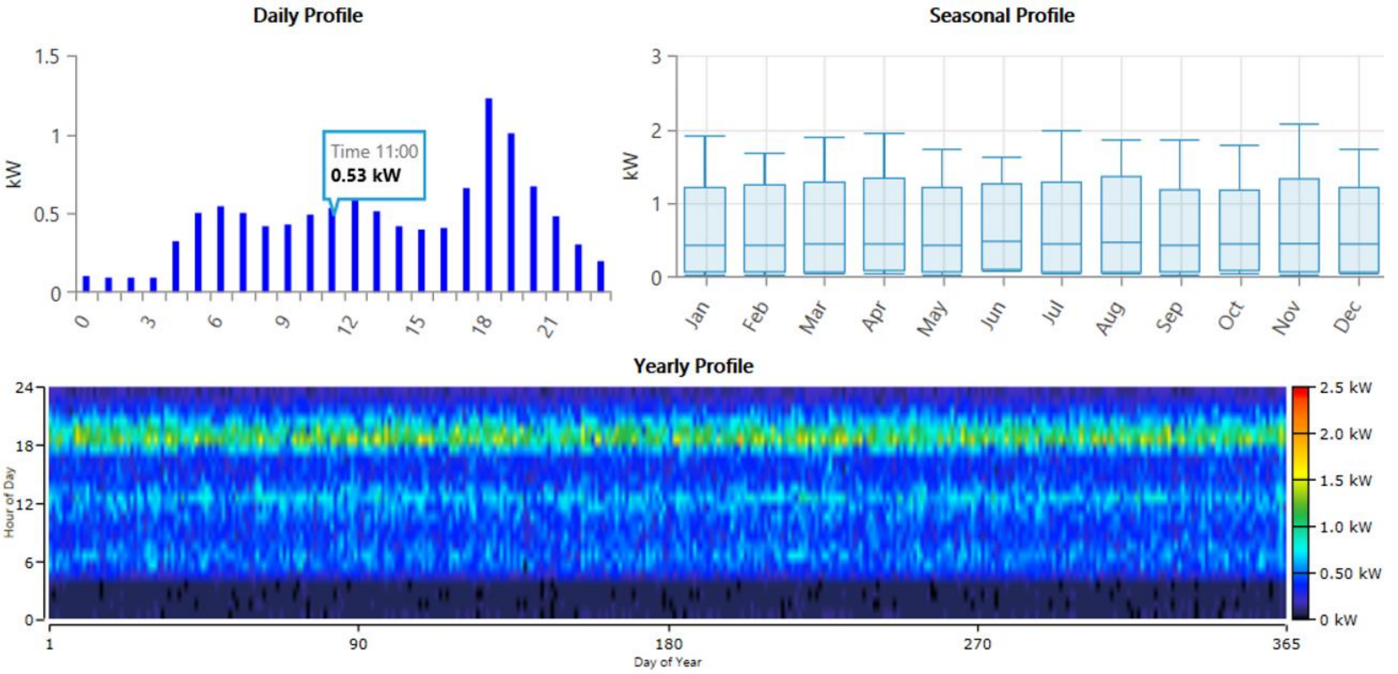

Figure 3. Electricity load in several areas of Maluku

Table 1. System components [26]

Parameter	Capital Cost	Replacement Cost	O&M (years)	Life Span (years)
PV flat plates	RP 9,840,188.00	RP 9,840,188.00	RP 149,320.00	25
Surette 8 CS 25P	RP 30,821,000.00	RP 26,775,000.00	RP 107,000,000.00	15
Generic Converter	RP 9,639,000.00	RP 8,895,250.00	RP 82,126.00	20
Generic Generators	RP 3,285,040.00	Rp.2,986,400.00	RP 3,810,240.00	15

Figure 4 shows the average monthly temperature in several areas that are the research subject in Maluku Province. The figure shows that the highest average temperature is in Tual in May at 24.63 ℃. Figure 5 shows the average wind speed in months. It can be seen that the highest average wind speed was in the city of Tual in February and March at 2.26 m/s. Figure 6 shows the average intensity of solar radiation each month. It can be seen that the highest average intensity of solar radiation is in the city of Tual, also in October, which reaches a value of 6.53 kWh/m^2.

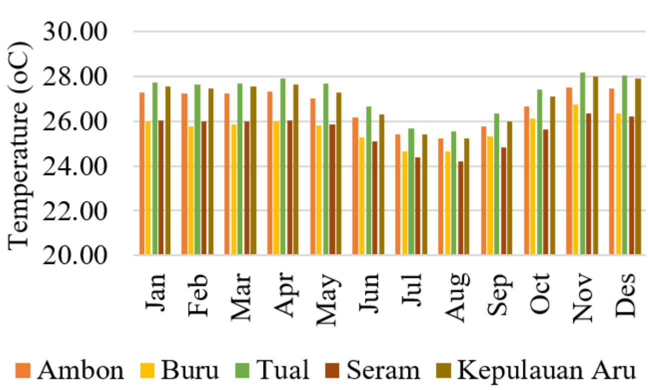

Figure 4. Average ambient temperature for a month

Some environmental parameters can significantly affect the system's performance, given that solar panels are highly influenced by sunlight intensity and wind speed. High sunlight intensity will produce more energy from the solar panels, while high wind speed can help cool the solar panels and improve their efficiency. Meanwhile, environmental temperature also has a crucial impact on the lifespan and durability of the generator.

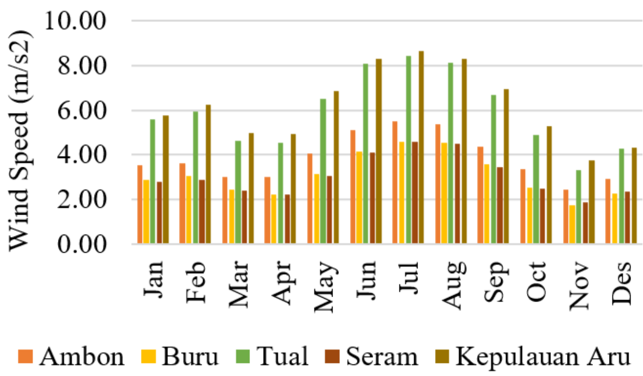

Figure 5. Average wind speed in a month

High environmental temperatures can accelerate the occurrence of degradation in system components, potentially reducing their lifespan and increasing the risk of damage. Therefore, paying attention to the proper system arrangement is essential to keep the temperature of generators and solar panels within safe limits. Considering these environmental factors is crucial in designing and operating renewable energy systems. With a good understanding of how environmental parameters affect system performance, we can optimize the design and operation of the system to achieve maximum and long-term efficiency.

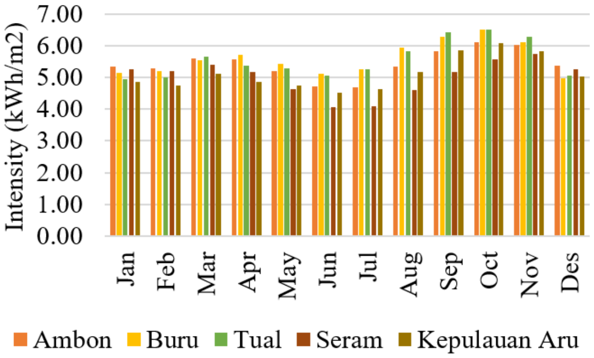

Figure 6. The average intensity of solar radiation in a month

Based on the data from the tables above, the city of Tual has the most significant potential for development with suitable environmental parameters as the initial development of this hybrid-PV technology. However, beyond that, several other parameters are still considered in conducting this study. Electrical charges and costs are also used as input information for HOMER [17].

2.4 Economic analysis

The examination of output power takes the form of electricity produced by solar panels and generators. In comparison, the cost analysis includes the cost of energy (COE) and the net present cost (NPC) [27]. Due to its success in generating precise cost estimates for renewable energy projects, the economic analysis employing the feasibility approach using NPC and COE is commonly used in HOMER. In order to examine the project's economic sustainability, this method looks at a variety of financial factors, including the original investment, ongoing expenditures, maintenance costs, and possible income production.

The feasibility analysis in HOMER considers factors like solar resource availability, load demand patterns, fuel prices, and technology costs to predict the system's performance and long-term economic benefits accurately. With such reliable cost estimations, stakeholders can make informed decisions about investing in renewable energy projects, fostering the sustainable development of energy infrastructure in Indonesia, and contributing to the national electrification efforts.

The output power of the PV panel is calculated using Eq. (1) as shown below.

$$P_{PV} = Y_{PV} \times f_{PV} \times \left(\frac{G_T}{G_{T,STC}}\right) \times \left[1 + \alpha_P\left(T_c - T_{c,STC}\right)\right] \qquad (1)$$

where, Y_{PV} is the nominal capacity of the PV panel, f_{PV} is the reduction factor of the PV panel, G_T is the solar radiation received by the PV panel at the current time, $G_{T,STC}$ is the radiation received by the PV panel at standard conditions, α_P is the temperature coefficient of power, T_c is the temperature of the PV panel at the current time, and $T_{c,STC}$ is the temperature of the PV panel under standard test conditions.

Eq. (2) below is used to calculate the output power of a wind turbine.

$$P_{WTG} = P_{WTG,STP} \times \left(\frac{\rho}{\rho_0}\right) \qquad (1)$$

where, P_{WTG} is the power generated by the wind turbine, $P_{WTG,STP}$ is the power generated by the wind turbine under standard conditions, ρ is the actual density of air, and ρ_0 is the density of air at standard conditions [28].

The total net present cost (NPC) is calculated using Eq. (3) below.

$$NPC\ (Rp) = \frac{TAC}{CRF} \qquad (3)$$

where, *TAC* are the total annual cost and *CRF* the payback factor calculated using Eq. (4).

$$CRF\ (Rp) = \frac{i(1+i)^N}{[(1+i)^N - 1]} \qquad (4)$$

where, *i* is the number of years, and *i* is the range of genuine annual interest (%). COE energy cost is the average unit cost of energy produced (Rp/kWh), which is calculated using Eq. (5).

$$COE\ (Rp/kWh) = \frac{C_{tot.ann}}{E} \qquad (5)$$

where, $C_{tot.ann}$ is the total annual cost, and *E* is the total energy consumption per year [29].

According to the Central Statistics Agency (BPS) in Figure 7, Maluku had a BI discount rate of 5.75% in April 2023 [30]. Apart from that, Maluku also has an inflation rate of 4.01% in 2021 [31]. The projected lifespan of this hybrid system is 20 years.

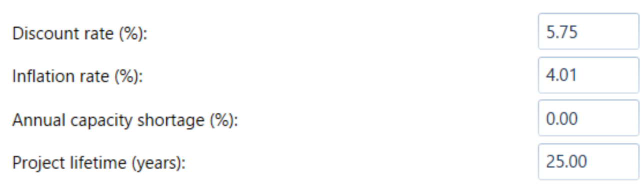

Figure 7. Annual inflation

3. RESULTS AND DISCUSSIONS

In this section, we will go through the outcomes of our techno-economic analysis calculations and our efforts to maximize solar PV systems that are connected to generators. Following a brief presentation of the techno-economic study' findings, the optimization outcomes are next briefly addressed.

3.1 Electrical generation

The proposed scheme is assembled before carrying out a simulation using HOMER. The proposed PV-generator hybrid systems have the exact specifications and costs for each predetermined area. The system connected to the leading network consists of PV panels, generators, converters, and batteries, as shown in Figure 8. Based on the results of the environmental conditions carried out in the five cities in the Maluku area, Tual City has the most significant development potential, so this discussion is the result of system optimization and techno-economic analysis conducted in Tual City, Maluku province.

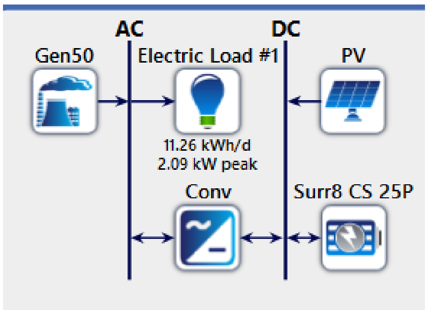

Figure 8. Proposed hybrid system setup

Figure 9 shows the results of the power output generated by the solar panels used. In this system, the average nominal power production per day is obtained at a value of 1.08 kW with optimal results from 07.00 to 17.00 in that time zone, which can achieve daily production of up to 5.79 kW. With an annual production of 9,457 kWh/yr. Table 2 shows the results of the simulation of the output power in this system using the Homer application.

Table 2. PV output values

Quantity	Value
Rated Capacity	5.79 kW
MeanOutput	1.08 kW
Mean Output(daily)	25.9 kWh/d
Capacity Factor	18.6%
Total Production	9,457 kWh/yr

Meanwhile, the diesel system integrated with PV can produce an average output power of 0.469 kW with a maximum value of 2.09 kW. Figure 10 shows the annual production of a generic diesel generator with a capacity factor of 21.8%, as shown in Table 3.

Table 3. Generator output value

Quantity	Value
Capacity	2.15 kW
MeanOutput	0.469 kW
maximum output	2.09 kW
Capacity Factor	21.8 %
Hours of Operation	8,757 hrs/yr
Energy Out	4.107 kWh/yr
Energy In	4,323 kWh/yr
Losses	216 kWh/yr

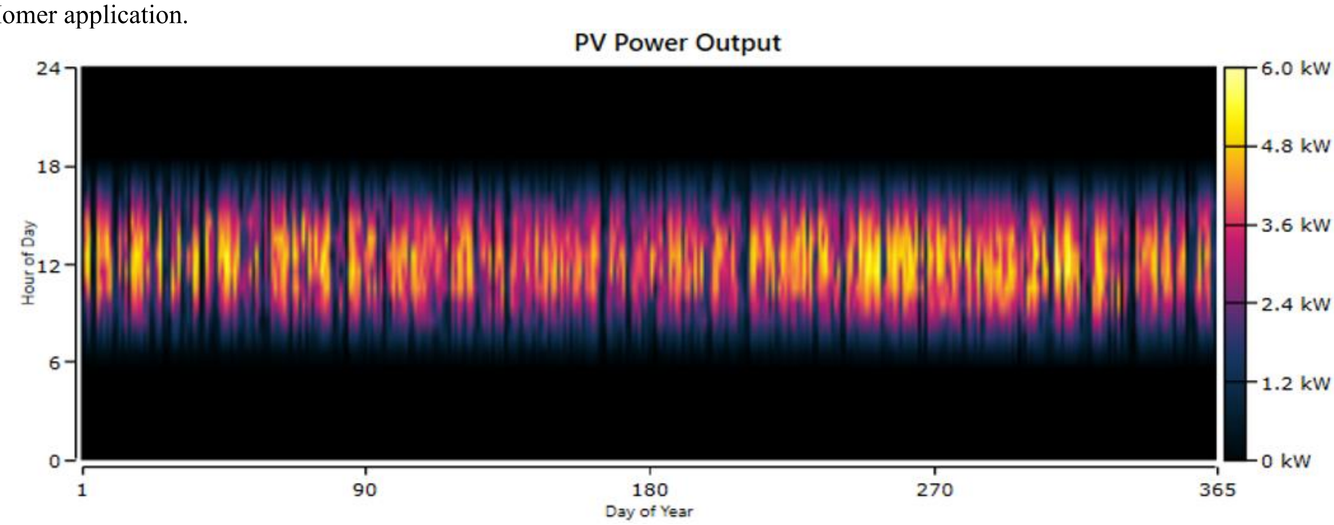

Figure 9. Solar PV outputs

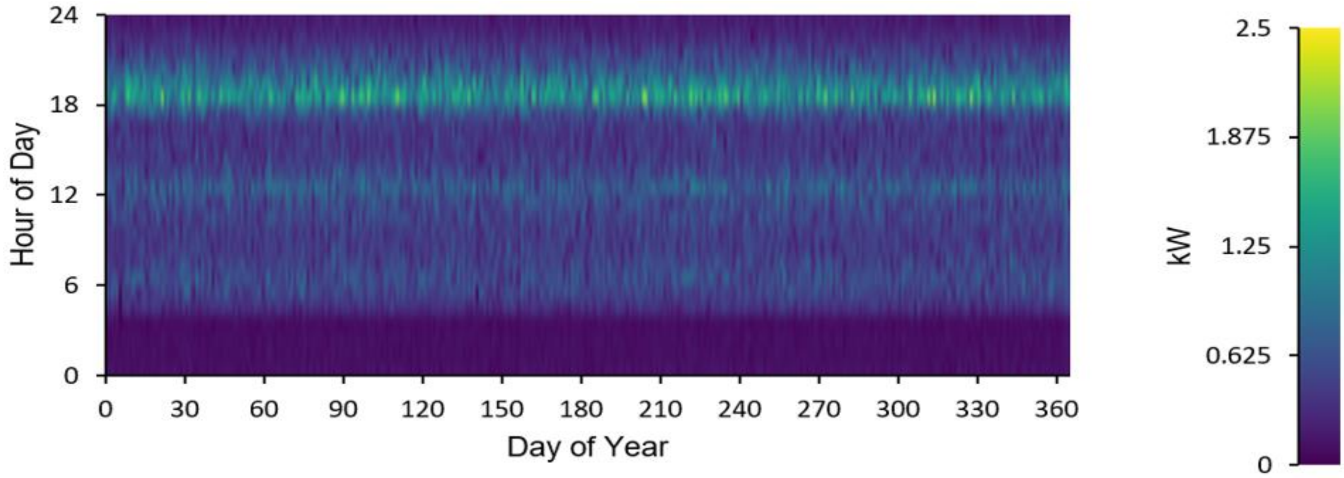

Figure 10. Generic diesel output

3.2 Techno-economic analysis

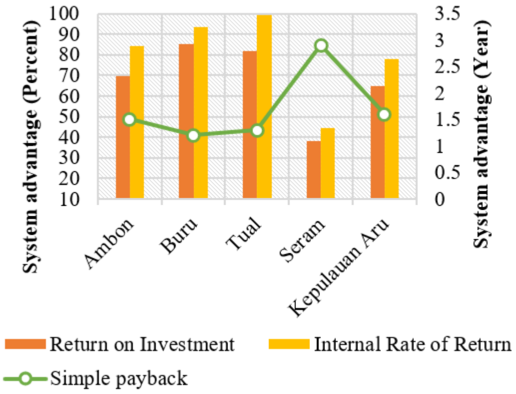

Figure 11. Comparison of economic metrics

Figure 11 above shows that the city of Tual has the most significant percentage of Return on Investment (ROI) and Internal Rate of Return (IRR) compared to other regions, with a ratio of 99% ROI and 82% IRR. In contrast, Seram has the most significant annual simple payback value. Based on the data above, the city of Tual is the area that has the best configuration for the PV-generator hybrid system. In addition, it is essential to compare NPC values as a basis for techno-economic analysis, as shown in Figure 12.

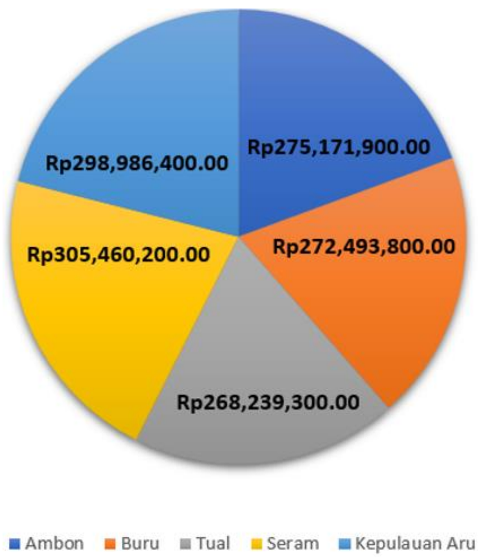

Figure 12. Comparison of NPC values

From Figure 12, the city of Tual is suitable for many potentials, as seen from the lowest total NPC [32]. The system with the lowest NPC value is recommended by the HOMER application and has the best configuration [33]. Details of the total cost of NPC in the city of Tual during the application of this system can be seen in Table 4.

Table 4. Details of the total cost of NPC in the city of Tual

Components	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic flat plate PV	RP 57,001,782.66	Rp0.00	RP 17,554,077.65	Rp0.00	Rp0.00	RP 74,555,860.31
System Converter	RP 20,764,891.52	RP 13,751,505.64	RP 3,590,486.92	Rp0.00	-Rp 9,492,598.59	Rp28,614,285.49
Surrette 8 CS 25P	Rp123,284,000.00	RP 76,857,079.46	RP 18,182,107.59	Rp0.00	-Rp 53,054,074.44	RP 165,269,112.61
System	Rp201,050,674.19	Rp90,608,585.10	Rp39,326,672.16	Rp0.00	-Rp 62,546,673.03	Rp268,439,258.41

From the details of NPC costs in Table 2, a total system cost of Rp. 268,439,258.41 is obtained with annual operational costs of Rp. 3,220,560.00. In addition, energy costs have been optimized with a system with a value per kWh of Rp. 3,220.56. The value of the generated electricity per kWh is more than twice as expensive as the price sold to Indonesian people from PLN, which is only Rp 1,500.00/kWh. In addition to the total cost of the NPC, there is also a breakdown of the annual cost of using the PV-wind turbine hybrid system components, which can be seen in Table 3.

Table 5. Details of the cost of using components every year

Components	Capital	Replacement	O&M	Fuel	Salvage	Total
Generic flat plate PV	RP 2,808,752.33	Rp0.00	RP 864,973.94	Rp0.00	Rp0.00	Rp3,673,726.27
System Converter	Rp1,023,186.20	RP 677,602.91	Rp176,920.58	Rp0.00	-Rp 467,746.05	Rp1,409,963.64
Surrette 8 CS 25P	RP 6,074,796.37	RP 3,787,118.42	Rp895,920.00	Rp0.00	-Rp 2,614,229.74	Rp8,143,605.06
System	Rp9,906,734.91	Rp4,464,721.33	Rp1,937,814.52	Rp0.00	-Rp 3,081,975.78	RP 13,227,294.98

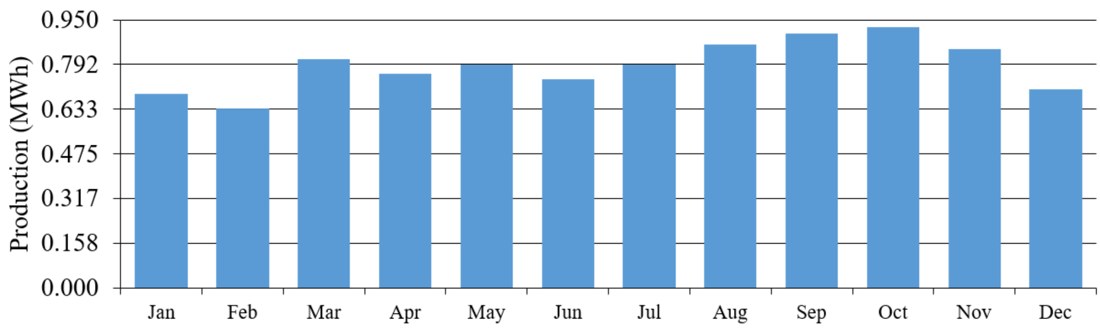

Figure 13. Monthly electricity production

The details of the total NPC costs in Table 2 show all costs used during this HRES system allocated for 25 years. While Table 5 shows the average cost each year of using components during the year. O&M (Operational and Maintenance) costs yearly, PV panels RP 864,973.94/year, batteries RP 895,920.00/year, and converters RP 176,920.58/year. It is known that PV panels have the highest O&M costs compared to other components. PV panels do not require component replacement because they have a lifetime of 25 years, according to the proposed project period. While the Surette 8 CS 25P battery has a lifetime of 15 years, so it requires a replacement cost of Rp. 3,787,118.42.

In addition to cost analysis, there is also an output power analysis. The monthly output of electrical energy from the PV-generator panel per month is shown in Figure 13. From this figure, it can be seen that the electrical energy generated by the PV panels is influenced by the geographical conditions of the environment, as explained in Figures 4-6. Total electrical energy supplied generated per year of 9,457 kWh/year.

A hybrid power generating system using solar energy and generators is quite possible to deploy in the city, according to the modeling findings from the HOMER program. The other primary components don't need to be replaced since they have a lifespan and operating hours greater than the project's running duration, requiring just a little amount of maintenance during the project's 25-year lifespan.

The main goal of sensitivity analysis is to foresee and comprehend how variations in values during the ensuing years may impact the effectiveness and performance of the hybrid power production system. Two particularly important sensitivity variables are daily load usage and gasoline prices. It is crucial to take uncertainties in cost estimates and fuel supply into account since changes in these two variables can have a major influence on how the system is configured and operated. According to the simulation findings, the hybrid power production system's parts will be worth more after the project is finished. This shows that there is strong long-term return potential for investing in this hybrid system. Future efficiency gains and technological advancements should lower the investment cost for the hybrid system's component parts, making it even more alluring to financiers and those in charge of developing renewable energy projects.

A profound understanding of the various analyses in this research is hoped to provide a better strategy for developing sustainable and efficient hybrid power generation systems in remote areas. Using renewable energy sources and hybrid systems represents a crucial step toward Indonesia's more sustainable and environmentally friendly future.

4. CONCLUSIONS

Grid-connected and off-grid hybrid power systems are compared in the extensive study carried out at Seram City. According to the optimization results, a diesel generator linked to the off-grid is more efficient and economical than a normal PV system at the same load. The region's favorable geography with high solar intensity presents significant potential for developing solar energy in underdeveloped areas. Additionally, environmentally friendly renewable energy sources can be expanded to support Indonesia's national electrification program, especially in remote and underserved regions where conventional power systems are not accessible.

The economic performance of the renewable energy system is examined using feasibility analysis based on the evaluation's findings. The economic advantages of the proposed system are calculated by factoring in system running expenses, initial investment costs, and replacement costs. This study takes into account every expense made during the system's lifetime. The most lucrative mechanism in the HOMER model is chosen depending on the NPC value. To rate every scenario with different settings and identify the smallest one, optimization uses NPC. Based on the simulation results from the HOMER application, the city of Seram has the best configuration system for a PV-wind turbine hybrid system because it has a total of RP 268,439,300.00 and a Cost of Energy (COE) of RP 3,220.56. The total electricity generated is 9.457 kWh/year, with operational costs of RP 3,220,560.00 per year. This research is expected to assist in developing renewable energy systems by providing mapping and references related to suitable systems to be implemented in underdeveloped areas.

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