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Economic Feasibility of a PV-Wind Hybrid Microgrid System for Off-Grid Electrification in Papua, Indonesia

Dominicus Danardono Dwi Prija Tjahjana, Suyitno, Rendy Adhi Rachmanto, Wibawa Endra Juwana, Yudin Joko Prasojo, Singgih Dwi Prasetyo, Zainal Arifin*

Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

Corresponding Author Email: zainal_arifin@staff.uns.ac.id

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ABSTRACT

Electricity is fundamental to both urban and rural livelihoods. However, with the impending depletion of fossil fuels, an urgent transition towards sustainable and environmentally friendly renewable energy sources is necessary for electricity generation. The Hybrid Renewable Energy System (HRES), which amalgamates various renewable energy sources, offers a promising solution. This study investigates the economic viability of a photovoltaic (PV)-wind turbine hybrid microgrid system for off-grid electrification in five distinct cities in Papua, Indonesia. A simulation of the hybrid system was conducted using the Hybrid Optimization Model for Electric Renewable (HOMER) application, leveraging local solar and wind resource data. The simulation results indicated that Waropen city yielded the most optimal PV-wind turbine hybrid system, exhibiting the lowest Net Present Cost (NPC) of Rp397,591,000.00 and Cost of Energy (COE) of Rp 5,513.37/kWh. This system was capable of generating 9,098 kWh/year of electricity. Consequently, the proposed PV-wind turbine hybrid microgrid system emerges as an economically feasible solution for off-grid electrification in Papua, underscoring the potential of renewable energy sources in addressing the global energy crisis.

1. INTRODUCTION

Electricity has become an indispensable aspect of modern society, with its demand escalating rapidly in both urban and rural sectors [1]. This surge in demand can be attributed to an increasing populace and the concomitant need for electrical energy. However, electrical energy generated from fossil fuels has come under scrutiny due to its significant contribution to greenhouse gas emissions, especially carbon dioxide, which exacerbates global warming and catalyzes extreme climatic changes worldwide [2]. Consequently, a paradigm shift towards renewable energy sources to replace fossil fuels for electricity generation has emerged as an urgent global necessity. Developed nations have already begun harnessing renewable energy, setting a precedent for developing countries to follow [3]. However, the unpredictable nature of renewable energy often results in oversized system designs, leading to increased costs. The Hybrid Renewable Energy System (HRES), which amalgamates multiple renewable energy sources with a battery or generator for storage, has been proposed as a cost-effective solution. This system has the potential to provide electricity to remote areas with limited or no access to electricity [4].

Endowed with abundant solar and wind energy, Indonesia presents a promising landscape for clean renewable energy [5]. The country's western region receives approximately 4.5 $kWh/m^2/day$ of solar radiation, while the eastern region receives around 5.1 $kWh/m^2/day$, resulting in an average potential of approximately 4.8 $kWh/m^2/day$ [6]. Furthermore, wind energy in Indonesia can also be used as alternative energy with an average wind speed ranging from 2 m/s - 7 m/s, small and medium-scale wind power plants are well suited for deployment in Indonesia [7].

Among the Indonesian regions with substantial solar energy potential, the province of Papua stands out. Despite its rich renewable energy resources, including solar and wind energy, Papua remains an underdeveloped region with limited access and uneven electrification conditions [8]. With an electrification ratio below 50%, significantly lower than the national average of 88.30%, Papua's geographical and demographic challenges, including mountainous terrain and low population density, contribute to its underdevelopment [9].

To harness Papua's renewable solar and wind energy resources, the implementation of a Hybrid Renewable Energy System (HRES) that melds these two energy sources into an off-grid Photovoltaic (PV)-wind turbine system has been proposed [10]. Off-grid electricity generation offers a potential solution for remote areas with limited or no access to electricity, such as Papua [11]. However, given the intermittent operation of PV and wind turbines, the inclusion of batteries in the system is essential to mitigate potential disruptions. The configuration of the proposed PV-wind turbine-battery hybrid system was modeled using the Hybrid Optimization Model for Electric Renewable (HOMER) software [12], which was employed to analyze the techno-economic feasibility of the proposed hybrid configuration system [13].

There are many studies analyzing the economic feasibility of PV hybrid systems for off-grid areas in Papua. Several studies on off grid PV systems have been studied for Papua province. Wicaksana et al. [14] conducted a study of a PV-generator-battery hybrid system using Homer Pro and Simulink in Amaru village, Asmat, Papua with project lifetime 25 years. The results obtained were NPC of Rp465,784,400.00 and LCOE of Rp5,127.00/kWh. This system generated 6,465 kWh/year of electricity. Arthanto et al. [15] conducted a study of off-grid PV-battery systems using Homer Pro and MATLAB/Simulink for Communal Load at Jifak Village-Asmat Regency, Papua Province with project life time 25 years. The LCOE result of Rp13,557.00/kWh and NPC of Rp1,265,085,623.00 were obtained.

Furthermore, the proper configuration and optimization are also determined, then an adequate installation and operating system can be predicted. HOMER also evaluates materials, replacement, operation and maintenance, and fuel costs [16]. The present study aims to evaluate the economic feasibility of a PV-wind hybrid microgrid system for off-grid electrification in five cities in Papua, Indonesia, using HOMER software. The city with the lowest Net Present Costs (NPCs) will demonstrate the most optimized system configuration [17]. This paper is divided into four sections: introduction, methods and materials, results and discussion, and conclusion.

2. MATERIALS AND METHODS

2.1 Regional selection

Papua province, with the districts of Intan Jaya, Yahukimo, Waropen, Lanny Jaya, and Yalimo, is the chosen place for the case study. The province is included in underdeveloped regions based on Presidential Regulation Number 63 of 2020 concerning the Determination of Underdeveloped Regions for 2020-2024 [18]. The electrification ratio in Papua is only around 45.93%, which is dominated by oil-fired power plants and is considered very low [19]. In addition, Papua has limited access to developing conventional energy due to extreme topography and morphology. Therefore, it is necessary to develop electrical resources using renewable energy [20]. Table 1 below shows the geographic, demographic, and climatic information of 5 cities in Papua. This data was obtained from en-gb.topographic-map.com and www.tomorrow.io/weather.

Table 1. Characteristics of 5 cities selected

Area	Coordinate	Average Altitude (m)	Climate	
			Average Annual Preci-Pitation (mm)	Average Annual Highest Tempe-Rature (℃)
Intan Jaya	3.41016°S 136.70837°E	1,597	4,878	24.8
Yahukimo	4.887°S 139.52°E	1,320	9,861	23.5
Waropen	2.286°S 137.01837°E	276	3,292	30.8
Lanny Jaya	3.91244°S 138.28766°E	2,269	5,543	18.9
Yalimo	3.88333°S 139.68333°E	889	5,082	21.1

2.2 Model description

The HOMER application simulates the potential of a PV-wind turbine-battery hybrid power plant to calculate COE. The parameters considered include solar and wind energy, profile loads, technical and economic components, and location determination [21]. Figure 1 below is a framework for the HOMER simulation that was carried out.

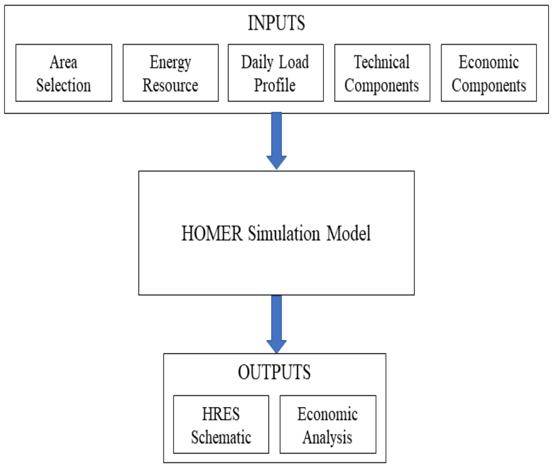

Figure 1. HOMER simulation framework

This simulation is performed to determine the area for techno-economic analysis (Figures 2-7). The areas selected in this study are 5 cities in Papua province. Then, determine the inflation rate and discount rate of Papua province which can be seen in Figure 7. The energy source for the selected area is obtained using the NASA Prediction of Worldwide Energy Resource (POWER) database in the HOMER application which can be seen in Figure 4, Figure 5, and Figure 6. Load profile is selected for residential with the default value of the HOMER application with peak month selected none with the results that can be seen in Figure 3. After that, select components in accordance with the hybrid system, determining the price, replacement, lifetime, and O&M as shown in Table 2. After that, a simulation with HOMER was carried out to obtain a schematic of the PV-wind turbine hybrid system and techno-economic analysis of the system. The data obtained was processed using Microsoft Excel.

The study of PV-wind turbine hybrid systems in several areas of Papua Province is illustrated in Figure 2. PV module and wind turbines are the sources of electrical energy used to transfer household electrical loads. The excess electrical energy generated is used to charge the battery bank. This charge uses a battery charger (charge controller) connected to the DC bus. The battery bank serves to store surplus electrical energy and to supply electrical loads when conditions of wind speed and solar radiation are low. The AC/DC inverter (converter) serves to convert the voltage from DC to AC so that it can be used in households. This system is simulated using the HOMER application to examine the costs required. Off-grid systems require an approach to assess costs because they rely on small energy systems such as PV panels, wind turbines, batteries, and other energy storage. Life cycle cost analysis (LCC) is an appropriate method in this system [22].

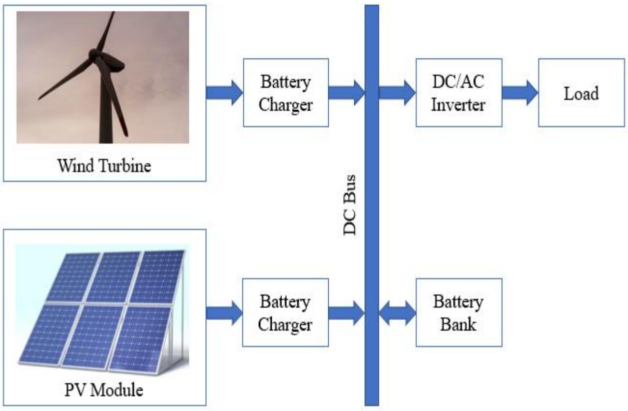

Figure 2. PV-wind turbine hybrid system configuration schematic

HOMER software validates electricity consumption by default for housing needs in Papua 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 [5]. Figure 3 shows the burden of household electricity consumption in Papua Province.

A PV-wind turbine hybrid off-grid system requires several components to operate correctly. In addition, these components influence the cost analysis to be carried out. The types and specifications of the components of this system are shown in Table 2.

2.3 Component specification

PV module, wind turbine, converter, battery are the components used to simulate the PV-wind turbine hybrid system. Based on market prices for Indonesia, the following are the specifications of the components used.

2.3.1 PV module

A flat plate type PV module with a capacity of 1 kW was selected with a capital cost of RP 18,275,400.00/kW. PV module replacement costs amounted to RP 18,275,400.00/kW. Meanwhile, the operation and maintenance costs amounted to RP 281,160.00/year. The lifetime of the PV module used is 20 years.

2.3.2 Wind turbine

An AWS type wind turbine with a capacity of 1.5 kW was selected with a capital cost of RP 48,500,100.00. Wind turbine replacement costs amounted to RP 31,630,500.00. As for the operation and maintenance costs of RP 843,480.00/year. The lifetime of the wind turbine used is 20 years.

2.3.3 Converter

A generic type of converter with a capacity of 1 kW was selected with a capital cost of RP 8,434,800.00/kW. The cost of replacing the converter is RP 8,434,800.00/kW. As for the operation and maintenance costs of RP 140,580.00/year. The lifetime of the converter used is 10 years.

2.3.4 Battery

A Surrette 4KS 25P type battery with a capacity of 7.55 kWh is selected with a capital cost of IDR 17,699,022.00. Battery replacement costs amounted to RP 15,463,800.00. As for the operation and maintenance costs of RP 70,290.00 / year. The lifetime of the battery used is 10 years.

2.4 Environmental parameters

Ambient temperature, wind speed, and solar radiation in various regions in Papua Province were obtained using NASA Prediction of Worldwide Energy Resource (POWER) in the HOMER application. Papua province is one of the remote areas where the need for electrical energy is urgent. 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 Papua Province will be selected to be the subject of this research.

Figure 4 shows the average monthly temperature in several areas that are the subject of research in Papua Province. The figure shows that the highest average temperature is in the city of Waropen in May at 24.63°C. Figure 5 shows the average wind speed in months. The highest average wind speed is in the city of Waropen in February and March at 2.26 m/s. Figure 6 shows the average intensity of solar radiation each month. The highest average intensity of solar radiation is in the city of Waropen, also in February and December, at 5.37 kWh/m^2.

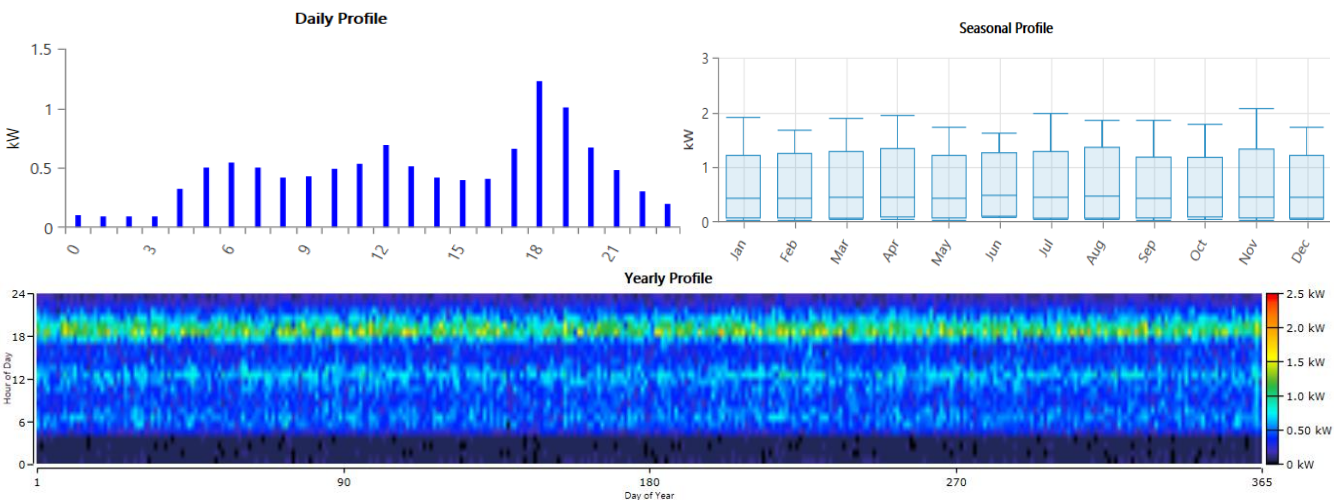

Figure 3. Electricity load in several areas of Papua Province

Table 2. System components [23]

Parameter	PV	Wind Turbine	Converters	Battery
Type	Flat Plates	AWS	generic	Surrette 4KS 25P
Rate Capacity	1 kW	1.5 kW	1 kW	7.55 kWh
Capital (Rp)	RP 18,275,400.00/kW	RP 48,500,100.00	RP 8,434,800.00/kW	Rp17,699,022.00
Replacements (Rp)	RP 18,275,400.00/kW	RP 31,630,500.00	RP 8,434,800.00/kW	RP 15,463,800.00
O&M (Rp/year)	RP 281,160.00/year	RP 843,480.00/year	RP 140,580.00/year	RP 70,290.00/year
Life Time	20 years	20 years	10 years	10 years

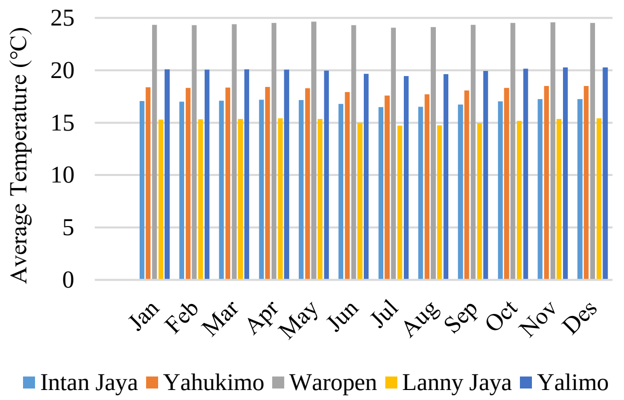

Figure 4. Average ambient temperature for a month

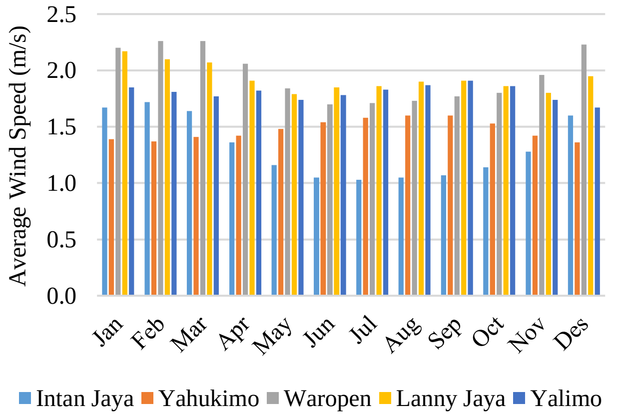

Figure 5. Average wind speed in a month

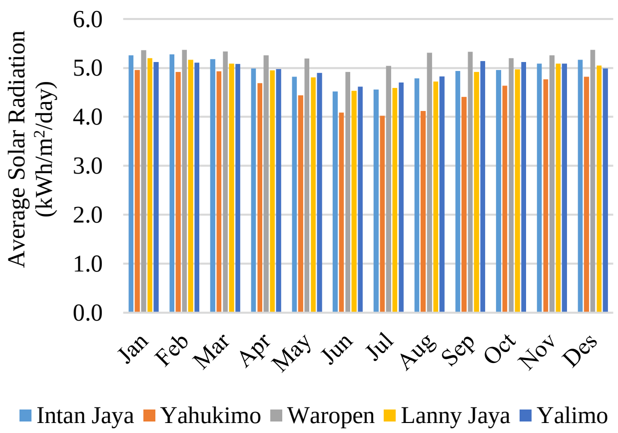

Figure 6. The average intensity of solar radiation in a month

Figure 7. Project assumptions

2.5 Economic analysis

The simulation results from HOMER have an economic analysis consisting of output power analysis and cost analysis. The output power analysis is in the form of power generated by PV panels and wind turbines, while the cost analysis consists of Net Present Cost (NPC) and Cost of Energy (COE) [24].

The following Eq. (1) is used to calculate the output power of the PV module.

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

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

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

$$P_{WTG} = P_{WTG,STP} \times \left(\frac{\rho}{\rho_0}\right) \quad (2)$$

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

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

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

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

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

where, N 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), calculated using Eq. (5).

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

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

According to the Central Statistics Agency (BPS), Papua had a BI discount rate of 5.75% in February 2023 [25]. In addition, Papua also had an inflation rate of 4.42% in March 2023 [26]. The projected lifespan of this hybrid system is 20 years.

3. RESULTS AND DISCUSSIONS

3.1 System configuration

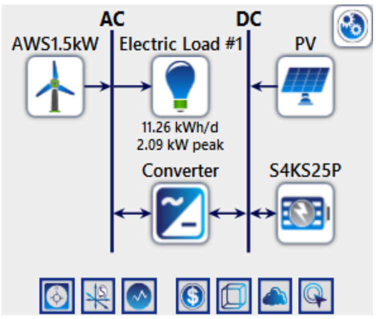

Figure 8. Proposed PV-wind turbine off-grid system

Techno-economic analysis simulations are carried out using HOMER with the proposed scheme first assembled according to the specified configuration. The proposed PV-wind turbine hybrid systems have the exact specifications and costs for each predetermined area. The system connected to the leading network consists of PV panels, wind turbines, converters, and batteries, as shown in Figure 8.

3.2 Optimization result

After the system has been assembled, conduct a simulation to produce an economic analysis of the proposed system. The results of the simulation carried out can be seen in Figure 9 below.

Figure 9 shows that the Yahukimo area has the highest total NPC, which is Rp.487,335,300.00, and the Waropen area has the lowest total NPC, which is Rp.397,591,000.00. Based on the data above, Waropen is the area that has the best configuration for a PV-wind turbine hybrid system. This can be seen from the lowest total NPC [17]. The system with the lowest NPC value is recommended by the HOMER application and has the best configuration [27]. Details of the total cost of NPC in the city of Waropen during the application of this system can be seen in Table 3.

From the details of NPC costs in Table 3, a total system cost of RP 397,590,971.27 can be rounded up to RP 397,591,000.00. In addition, an energy cost per kWh of RP 5,513.37 can be rounded up to RP 5,513.00/kWh. This price is much higher when sold to the public than conventional electricity from PLN, which is only Rp. 1,500.00/kWh [28]. 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 4.

The details of the total NPC costs in Table 3 show all costs used during the application of the HRES system, namely 20 years. While Table 4 shows the average annual cost of using components for 20 years. Annual O&M (Operational and Maintenance) costs for wind turbines are RP 843,480.00/year, PV panels RP 1,615,580.69/year, batteries RP 351,450.00/year, and converters RP 292,195.55/year. It is known that PV panels have the highest O&M costs compared to other components. PV panels and wind turbines do not require component replacement because they have a lifetime of 20 years, according to the proposed project period. At the same time, the battery has a lifetime of 10 years, so it requires a replacement fee of RP 3,880,150.

In addition to cost analysis, there is also an output power analysis. The monthly electricity output from PV panels and wind turbines is shown in Figure 10.

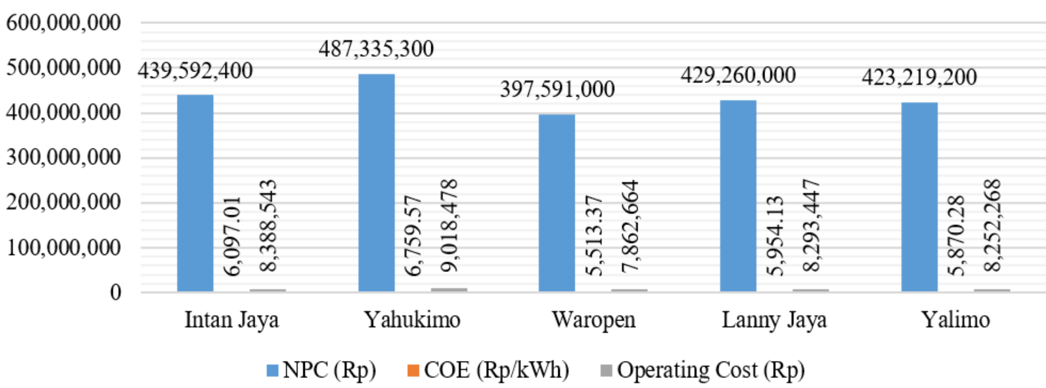

Figure 9. Comparison of NPC, COE, and operating costs in each region

Table 3. Details of the total cost of NPCs in the city of Waropen

Components	Capital	Replacement	O&M	Fuel	Salvage	Total
AWS HC 1.5kW Wind Turbine	RP 48,500,100.00	Rp 0.00	RP 14,809,675.45	Rp 0.00	Rp 0.00	RP 63,309,775.45
Generic flat plate PV	Rp 105,012,744.81	Rp 0.00	RP 28,366,085.35	Rp 0.00	Rp 0.00	Rp133,378,830.16
Surrette 4 KS 25P	Rp 88,495,110.00	RP 68,127,014.39	RP 6,170,698.10	Rp 0.00	Rp 0.00	Rp162,792,822.49
System Converter	RP 17,531,732.78	RP 15,447,491.71	RP 5,130,318.69	Rp 0.00	Rp 0.00	RP 38,109,543.18
System	Rp 259,539,687.59	Rp 83,574,506.10	RP 54,476,777,59	Rp 0.00	Rp 0.00	Rp397,590,971.27

Table 4. Details of the cost of using components every year

Components	Capital	Replacement	O&M	Fuel	Salvage	Total
AWS HC 1.5kW Wind Turbine	RP 2,762,306.61	Rp 0.00	Rp 843,480.00	Rp 0.00	Rp 0.00	RP 3,605,786.61
Generic flat plate PV	RP 5,980,964.96	Rp 0.00	Rp 1,615,580.69	Rp 0.00	Rp 0.00	RP 7,596,545.65
Surrette 4 KS 25P	RP 5,040,208.72	RP 3,880,150.80	RP 351,450.00	Rp 0.00	Rp 0.00	Rp 9,271,809.53
System Converter	Rp 998,513.84	Rp 879,806.61	RP 292,195.55	Rp 0.00	Rp 0.00	RP 2,170,516.00
System	RP 14,781,994.14	Rp 4,759,957.41	RP 3,102,706.24	Rp 0.00	Rp0.00	Rp 22,644,657.79

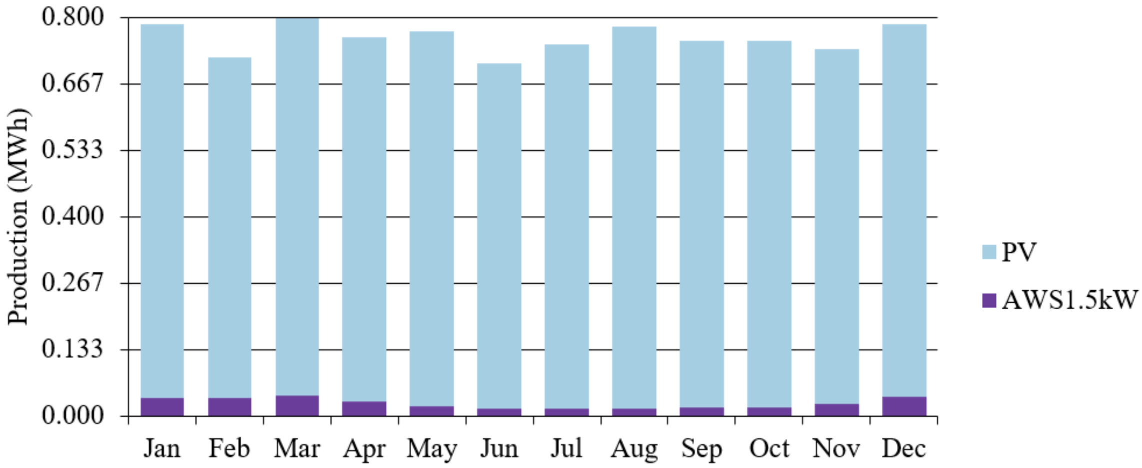

Figure 10. Monthly electricity production

3.3 Cost analysis

The figure shows that the electrical energy generated by PV panels is much greater than that of wind turbines. The production of electrical energy for each component of the PV panel and wind turbine is shown in Table 5. The total electrical energy generated per year is 9,098 kWh/year. Of the annual electricity production, PV panels have a percentage of 96.8% in meeting electricity needs. While wind turbines only play a role of 3.24% in generating electrical energy. So, PV panels have become the primary energy source in producing electrical energy to meet the electrical energy needs of the people of Waropen City.

Table 5. Annual production of PV panel electricity and wind turbines

Components	Production (kWh/year)	Percentage (%)
Generic flat plate PV	8,803	96.8
AWS HC 1.5kW Wind Turbine	295	3.24
Total	**9,098**	**100**

This hybrid system provides better results than previous studies conducted in Papua province as well. The previous study was conducted by Arthanto et al. [15] which is about off-grid PV modeling for Jifak village, Asmat Regency. The ability on a techno-economic analysis of the system's evaluation, taking into account various factors as specified in Eq. (1) and Eq. (3). Furthermore, it conducts energy optimization and return analysis for a duration of 25 years. HOMER is capable of performing all the necessary calculations and power collection procedures using relevant data. The limitations of this system are a discount rate of 4.75%, an inflation rate of 3.28%, and annual capacity storage of 5%. The results obtained were LCOE of Rp 13,557.00/kWh and NPC of Rp 1,265,085,623.00. These results are much higher than the hybrid system in this study. However, there are differences in the lifetime of the study conducted and the project assumptions. In addition, the specifications of the components used are also different.

4. CONCLUSIONS

This study shows a comparison of the techno-economic feasibility of PV-wind turbine hybrid microgrids for off-grid electrification in several cities in Papua, Indonesia. The data used in this study are obtained from HOMER application and the economic conditions of Papua province. At the same load, the PV-wind turbine hybrid configuration system in each city has different optimization. Based on the simulation results from the HOMER application, the city of Waropen has the best configuration system for the PV-wind turbine hybrid system because it has the lowest total Net Present Cost (NPC) of Rp 397,591,000.00 and Cost of Energy (COE) of Rp 5,513.37/kWh. The total electricity generated is 9,098 kWh/year. This system has a better configuration than previous studies in the Papua region with similar solar energy potential. However, it is also necessary to consider the specifications of the components used, lifetime, and cost. Therefore, studies on the techno-economic feasibility of PV hybrid systems for off-grid electrification in Papua can still be developed to get the most optimal PV hybrid system with more electrical energy generated with the lowest possible NPC. This study is expected to help explore the utilization of solar energy in locations that face challenges in accessing electricity.

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