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Economic Analysis of On-Grid Photovoltaic-Generator Hybrid Energy Systems for Rural Electrification in Indonesia

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ABSTRACT

The increasing demand for electrical energy is causing conventional energy supplies to become insufficient, leading to power outages especially in remote areas. Additionally, the reliance on fossil fuels for energy contributes to global warming. There is a pressing need for additional renewable energy sources to meet these energy needs. Hybrid Energy Systems (HES), which combine two or more energy sources, offer a promising solution. This study aims to analyze a PV-generator hybrid system connected to the grid in several cities in East Nusa Tenggara. The hybrid system configurations are modeled using the Hybrid Optimization Model for Electric Renewable (HOMER) software. Simulation results indicate that the performance varies across cities due to environmental parameters. Among the cities studied, Alor demonstrated the highest efficiency and best energy production according to economic analysis and energy output data.

1. INTRODUCTION

The growth of the human population, along with technological advancements and increasingly modern lifestyles, is driving up energy demand [1]. In Indonesia, energy needs continue to rise year by year. Conventional energy supplies, such as steam and diesel power plants, are becoming more necessary than ever. However, in some areas, particularly the most remote rural areas of Indonesia, electricity is still lacking, and power outages frequently occur due to insufficient electricity generation [2]. This highlights the need for a more efficient energy source to meet the increasing demand. Conventional power plants still rely on finite fossil fuels such as coal, gas, and oil, which emit significant greenhouse gases and contribute to global warming [3]. If this reliance on fossil fuels continues, it is predicted that the world will face severe disasters in the coming decades [4-6].

Renewable energy, obtained from naturally replenishing resources such as solar, wind, water, geothermal energy, and biomass, is seen as the right solution [7]. Being located near the equator, Indonesia has enormous potential for solar energy, which is a virtually infinite renewable energy source with minimal emissions [8]. Photovoltaic (PV) solar panels, which convert sunlight into electricity, could be particularly effective in areas of Indonesia that have many sunlit days, such as East Nusa Tenggara and Papua [9, 10].

Indonesia is in the form of an archipelago that stretches or extends. Expanding the national electricity network is challenging and has many problems. Therefore, renewable energy hybrid systems must be considered and developed significantly to compensate for the shortage of energy generated by power plants, especially in the outermost rural areas. In areas with a shortage of electricity, power outages often occur. Renewable resources are sometimes fluctuating and limited, making them less reliable because they are affected by natural conditions. This can be overcome by utilizing a Hybrid Energy Systems (HES) system [11].

Hybrid Energy Systems (HES) integrate two or more energy sources to satisfy electrical needs more efficiently and effectively than a single power source [12]. On a global scale, the primary role of HES is to ensure maximum energy production while maintaining service quality [13]. Environmentally, HESs can reduce greenhouse gas emissions by encouraging the use of renewable energy sources [14]. Furthermore, it has been demonstrated that HESs can effectively lower the overall life cycle cost of standalone systems in various scenarios, while also improving the reliability of electricity supply [15]. Energy management is a critical aspect of HES as it significantly influences the system's performance [16]. Improper configuration and management can cause the system to operate outside of safe parameters [17]. On-grid hybrid power generation systems have been widely implemented in numerous countries, particularly for smart cities [18]. Techno-economic analysis has validated the feasibility of implementing standalone, grid-connected hybrid energy systems. Furthermore, optimizing the size of each component can help to reduce system costs [19].

The main power plants in Indonesia use coal as the primary network [20], supplemented by renewable energy sources such as solar energy with photovoltaic technology. Diesel generators are also employed, and due to their lower emissions compared to coal, the government has allocated more subsidies for imported diesel [21]. These generators serve as a backup during power outages in the main network, ensuring uninterrupted energy supply.

The Hybrid Optimization Model for Electric Renewables (HOMER) software can be utilized to model these HES configurations [22]. HOMER can model hybrid systems from technological, economic, and environmental perspectives [23], simulating the performance of HES systems daily over the year based on energy supply sources and lifecycle costs [24]. This study aims to model the potential use of solar energy HES systems with photovoltaic-diesel generator technology connected to the grid in the outermost areas of Indonesia using HOMER software.

2. METHOD

2.1 Regional selection

NTT, or East Nusa Tenggara, is a province in Indonesia that is located east of the islands of Java and Bali. Geographically, NTT is between 7°08'-11°13' South Latitude and 116°33'-124°28' East Longitude. NTT is located around the equator, so the availability of sunlight throughout the year solar energy can be used as a substitute for conventional energy which is starting to be limited, and the price is relatively high. The electrification ratio value in East Nusa Tenggara is quite low, at 21.34%, due to the region consisting of small islands with limited access and infrastructure [25]. The potential for solar energy in NTT is 6.07 kWh/m^2, causing NTT to have the potential to utilize solar energy as a source of electrical energy [26]. It also has a large enough area with sufficient land to build solar panel installations. Limited and quite expensive conventional energy requires additional energy based on renewable energy with the HES system.

2.2 Model description

This research was carried out by modeling a Photovoltaic-Generator system connected to the network in several regions in NTT, namely Alor, East Sumba, Manggarai, Kupang, and Nagekeo for technological-economic analysis. This system is modeled with HOMER software.

HOMER software performs modeling and analyzes the techno-economic feasibility of the proposed HES configuration system [27]. Parameters considered in HOMER simulation modelling include profile loads, energy sources, technical and economic components, and location determination. Figure 1 below is the HOMER simulation framework that was carried out. A schematic diagram of the proposed HES system configuration is shown in Figure 2.

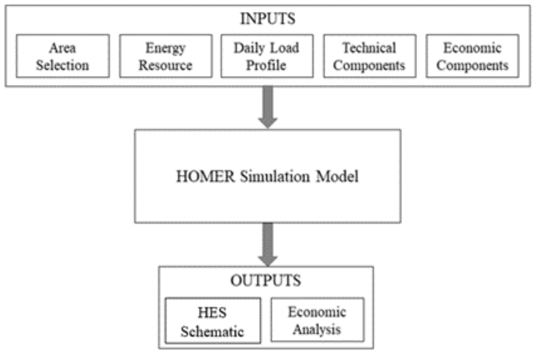

Figure 1. HOMER simulation framework

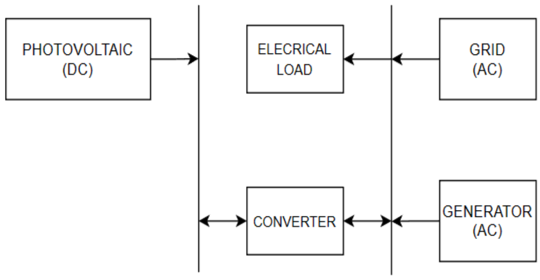

Figure 2. Schematic configuration of the on-grid PV-generator hybrid system

The average consumption load was obtained for each region in East Nusa Tenggara, assuming the average usage in Indonesia was 11.26 kWh/day, with the maximum load being 2.09 kW. The estimated electrical load profile is validated by Homer software is shown in Figure 3. This electricity consumption expense is calculated for each month [28]. The network input parameters include electricity prices and network selling prices, which are set by the central government. The selling price set by the government is Rp 911.00 while the price of network electricity is Rp 1,500.00 [29].

A grid-connected PV-Generator Hybrid System requires several critical components to establish the best design and cost. The main components of the hybrid system are connected to the PV circuit network, generator, and converter. Table 1 shows the types and specifications of the components of this system.

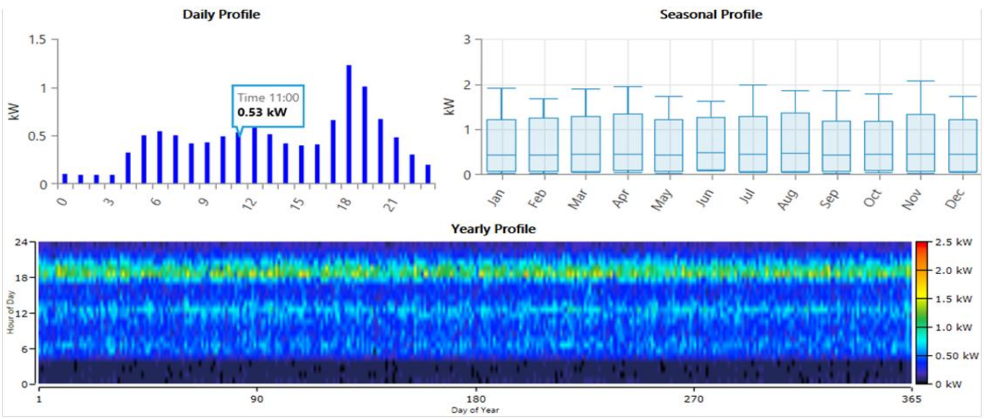

Figure 3. Estimated electric load profile in East Nusa Tenggara

Table 1. System components [3]

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
Generic Converter	Rp 8,434,800.00	Rp 8,434,800.00	Rp 140,580.00	20
Generic Generator	Rp 7,425,500.00	Rp 7,425,500.00	Rp 3,810,240.00	15

2.3 Environmental parameters

Environmental parameters are factors that influence environmental conditions in an area to determine the renewable energy potential of that area. In order to assess the renewable energy potential of the East Nusa Tenggara region and identify areas with a comparative advantage, various environmental parameters have been considered. These parameters include solar irradiance, and temperature. By analyzing and comparing these parameters, it is possible to identify specific areas within the region that have a higher potential for harnessing renewable energy resources. This information will assist in directing future energy planning and development strategies, as well as ensuring the optimal utilization of hybrid energy systems from renewable energy sources in East Nusa Tenggara. Data on environmental temperature and solar radiation in several areas in East Nusa Tenggara were obtained from NASA predictions of worldwide energy resources, which can be obtained from the resources feature in design HOMER. This data is needed to determine the energy potential characteristics of each region from environmental parameters.

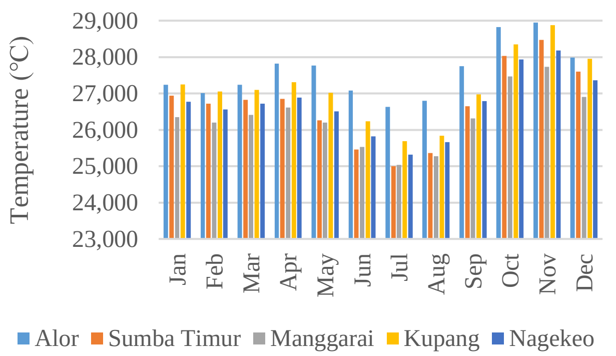

Figure 4. Average ambient temperature in east Nusa Tenggara

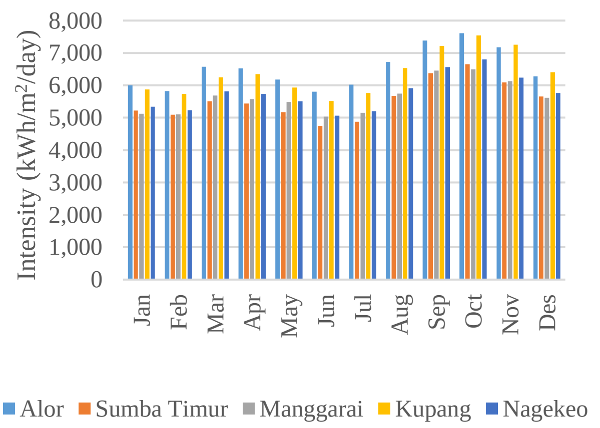

Figure 5. The average intensity of solar radiation in east Nusa Tenggara

Figure 4 shows the average monthly temperature data in several areas that are the research subject in East Nusa Tenggara Province. From the figure, it can be seen that the highest average temperature is in the city of Alor in November at 28.880°C. Figure 5 shows the average intensity of solar radiation each month in East Nusa Tenggara. It can be seen that the highest average intensity of solar radiation is in the city of Alor, also in October, at 7.61 kWh/m^2. Photovoltaic systems use solar cell technology to convert photons in sunlight directly into electricity [30]. From these environmental parameters, it can be concluded that the city of Alor is a city that has the best potential compared to others to become the initial place for installing a hybrid PV-generator system with an on-grid system.

2.4 Economic analysis

Economic analysis in HOMER refers to the process of evaluating the financial aspects of hybrid renewable energy systems using the HOMER software. In the context of HOMER, economic analysis involves considering parameters such as capital costs, operating and maintenance expenses, fuel costs, equipment lifetimes, nominal discount rate, the anticipated inflation rate, and the project's lifespan. These parameters are inputted into the software to simulate and optimize the energy system's design and operation.

Figure 6. Economic data

Overall, economic analysis in HOMER Pro plays a crucial role in guiding decision-making processes by providing insights into the economic feasibility, cost-effectiveness, and financial performance of hybrid renewable energy systems. It helps stakeholders, policymakers, and investors make informed decisions and optimize the design and operation of sustainable energy. Figure 6 displays the economic data required for this study in several East Nusa Tenggara areas.

The simulation results from the HOMER application have an output in the form of economic analysis. The cost of the system is determined through the cost of capital owned (Rp), component replacement costs (Rp), and operation & maintenance costs (Rp/year).

2.4.1 Net present cost (NPC)

The present value of all costs incurred during a system's lifetime, less the present value of all revenue received over the same lifetime, is the system's total net present cost (NPC). The cost includes fuel prices, environmental penalties, operating and maintenance expenses, capital expenditures, replacement costs, and grid energy costs. Two sources of income are residual value and money made from selling power to the grid. The cumulative discounted cash flows for each year of the project life cycle are added to determine the total NPC [3].

The total net present cost (NPC) is calculated using Eq. (1) below.

$$NPC\ (Rp) = \frac{TAC}{CRF} \tag{1}$$

TAC is the total annual cost, and CRF is the payback factor. The capital recovery factor is the ratio used to determine the annual present value (a series of equal annual cash flows) calculated using Eq. (2).

$$CRF\ (Rp) = \frac{i(1+i)^N}{[(1+i)^N - 1]} \tag{2}$$

i is the range of genuine annual interest (%) and N is the number of years.

2.4.2 Cost of Energy (CoE)

The system may employ the Levelised Cost of Energy (CoE), which is the average cost per kWh of electrical energy that can be determined using the HOMER program. The cost of electricity (CoE) is calculated by dividing the yearly cost of producing electricity by the total cost of consuming the thermal load. Eq. (3) is used to determine CoE.

$$COE\ (Rp/kWh\ ) = \frac{C_{tot.ann}}{E} \tag{3}$$

2.4.3 Salvage value

Salvage value is the value of the generating system components that can still be used at the end of the project's life. The HOMER software uses the following equation to determine the value of each component after the project's life ends. The salvage value can be calculated by Eq. (4).

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{4}$$

S is the residual value, R_{rem} is the component life remaining, and R_{rem} is the component life.

2.4.4 Internal rate of return (IRR)

The discount rate at which net cash balances the base case system and the optimized system is the internal rate of return (IRR). The present value of the difference between two cash flow sequences divided by the discount rate yields the IRR.

2.4.5 Return on investment (ROI)

The yearly cost reductions over the original investment are known as return on investment (ROI). ROI may be computed by subtracting the yearly average difference in nominal cash flows throughout the project from the difference in the cost of capital. Eq. (5) may be used to determine the return on investment.

$$ROI = \frac{\Sigma_{i=0}^{R_{proj}} C_{i,ref} - C_i}{R_{proj}(C_{cap} - C_{cap,ref}\ )} \tag{5}$$

$C_{i,ref}$ is the nominal annual cash flow for the base system (reference), C_i is the nominal annual cash flow for the current system, R_{proj} is the project life in years, C_{cap} is the cost of capital of the current system, and $C_{cap,ref}$ is the cost of capital of the base system (reference).

2.4.6 Simple payback

Simple Payback is the period of time needed for the cumulative cash flow difference between the reference and the optimized case system to become positive. The amount of time needed to recoup the difference in investment expenses between the optimized case system and the base case system is known as the payback period [3].

3. RESULTS AND DISCUSSIONS

After the Hybrid Energy System (HES) Photovoltaic (PV)-Generator connected to the grid is assembled in the HOMER software, the obtained environmental parameters are simulated to generate the economic analysis of the system. This configuration consists of PV, generator, converter, and grid components. An overview of the proposed system configuration is depicted in Figure 7.

Figure 8 shows the outcomes of the simulation that was run. Figure 8 compares cost recovery statistics from each location over the last year. The profits realized are increased by a high rate of return on capital. Apart from environmental factors that might alter throughout the year, this profit margin determines the most advantageous site [29]. Each region exhibits distinct outcomes in the simulation of hybrid energy systems. This disparity arises from the diverse potential for energy source development in each respective area. Within this study, the potential of each region is illustrated by employing environmental parameters encompassing varying temperatures and average solar radiation intensity. In comparison to other cities, the Alor region has the potential for highly rapid economic expansion, according to the simulation findings. The city of Alor is an excellent choice for this study because of its economic potential. The city's environmental parameters, which include varied temperatures and the most significant average solar radiation intensity, are also highly favorable. The lowest overall NPC value among the other regions Rp 84,593,072.71 indicates this. A low NPC number means the suggested system configuration is the most effective and should be used [31]. The total NPC values in the Alor area and their details are shown in Table 2.

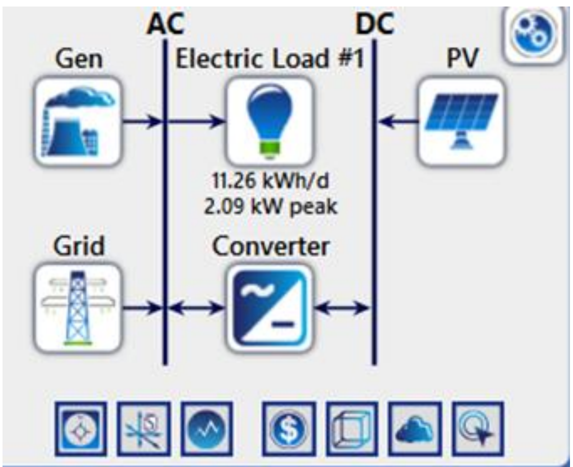

Figure 7. The proposed hybrid system configuration

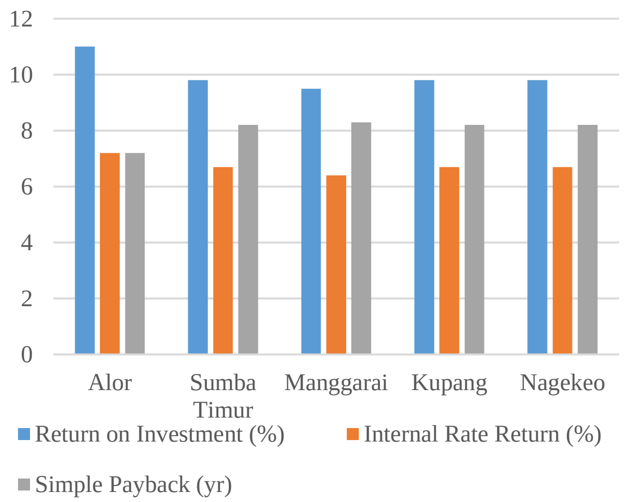

Figure 8. The proposed HES PV-Gen sequence

Based on the Total NPC in Table 2, the total system cost is Rp 84,593,072.71. The COE value obtained for buying energy per kWh is Rp 1,443.00. This shows it is cheaper than grid electricity sold at an energy price per kWh of Rp 1,500.00 [32]. The system financing flow over 25 years is shown in Figure 9. The financing flow depends on each component's capital, replacement, salvage, operational, and fuel values.

For the resilience and reliability of this system, each component has a lifespan and requires maintenance to ensure optimal performance. The estimated lifespan of 25 years is based on the average working life of solar panels that can work optimally. To reach 25 years of age, it requires some maintenance and replacement of components as shown in Table 2. The generator component is only used for emergencies when there is a network power outage at night due to high fuel costs. In addition, you still need to pay network electricity costs because this system uses a network-connected system. Based on Figure 8 in the city of Alor, the return on investment in this system is 7.2 years.

Table 2. Total value of NPCs in Alor

Components	Capital	Replacement	O&M	Salvage	Total
PV	Rp 12,129,895.00	Rp 3,867,099.82	Rp 2,379,505.67	Rp 2,179,358.75	Rp 16,197,142.17
Grids	0	0	Rp 43,162,076.99	0	Rp 43,162,076.99
Generator	Rp 17,078,650.00	0	0	Rp 3,989,041.56	Rp 13,089,608.44
System Converter	Rp 6,136,192.66	Rp 5,420,943.48	Rp 1,322,095.54	Rp 734,986.56	Rp 12,144,245.12
System	Rp 35,344,738.09	Rp 9,288,043.30	Rp 46,863,678.19	Rp 6,903,386.87	Rp 84,593,072.71

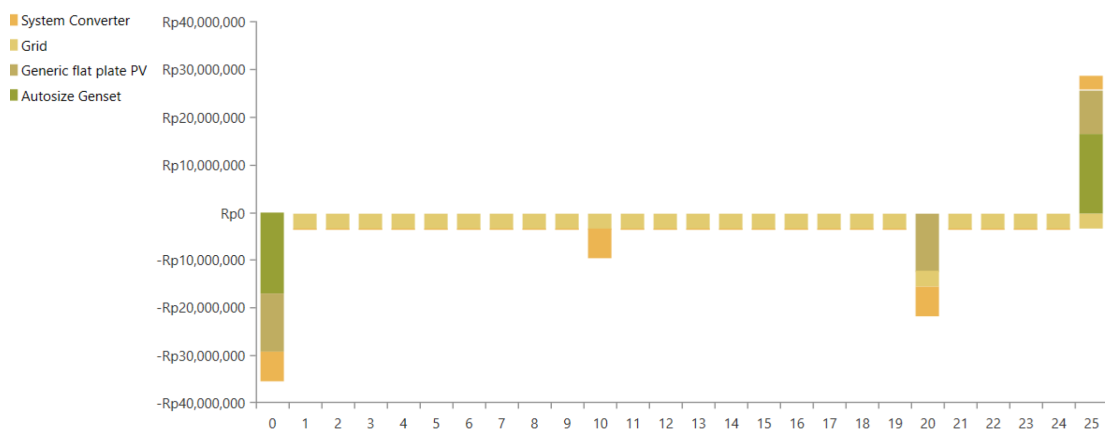

Figure 9. System financing flows for 25 years

The HOMER simulation results also analyze the power generated by each energy source. The average monthly electricity production from this system is shown in Figure 10. This figure shows that the electricity generated by the grid is greater than that of PV panels. For generators only for emergencies when there is a power outage, it is assumed that they will not work because of the high fuel cost, making it inefficient to use regularly. The total electrical energy generated per year is 4.85 kWh. From annual electricity production, PV panels have a percentage of 48.9% in meeting electricity needs. At the same time, the grid electricity source plays a role of 51.1% in generating electrical energy. Hence, producing electricity sources from solar and grid electricity is almost balanced. Electricity production and its percentages are shown in Table 3.

The environmental impact of using a hybrid energy system with an on-grid photovoltaic generator is the ability to reduce air emissions compared to conventional grid systems. This can be observed in Table 4, where simulation results show a significant reduction in air emissions, specifically Carbon Dioxide, Sulfur Dioxide, and Nitrogen Oxides, by 65% compared to conventional grid systems.

Table 3. Electrical energy production and annual percentage

Components	Production (kWh/year)	Percentage (%)
PV	2.37	48.9
GRID	2,481	51.1
Total	4.85	100

Table 4. Emission comparison

Emission	HES On-Grid PV-Gen	Conventionl Grid System
Carbon Dioxide	1,568	2,597
Sulfur Dioxide	6.8	11.3
Nitrogen Oxides	3.32	5.51

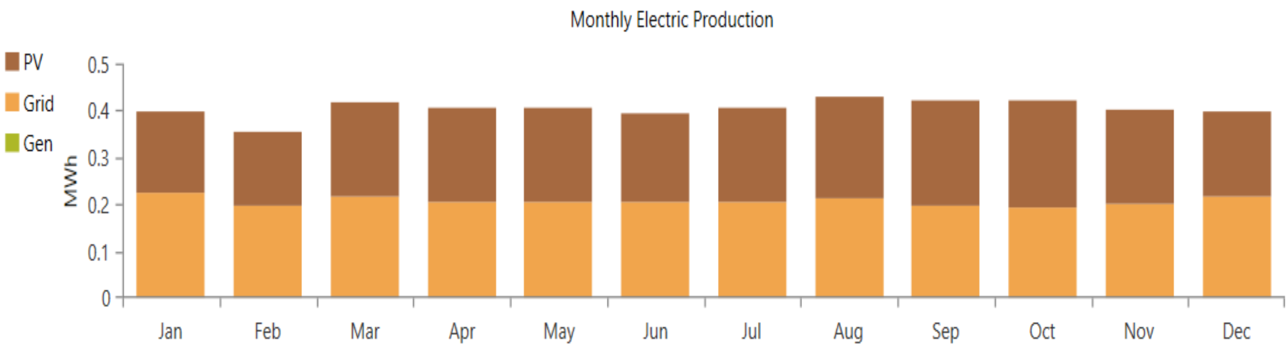

Figure 10. Average monthly electricity production

4. CONCLUSIONS

This study compares PV-Generator hybrid on-grid systems in several cities in the Province of East Nusa Tenggara (NTT), namely Alor, East Sumba, Manggarai, Kupang, and Nagekeo. NTT is the outermost area that has a problem with a shortage of electrical energy needs. Geographically, NTT has the potential to develop renewable energy sources with hybrid systems. Based on the results of simulation modeling using HOMER software under the same load conditions, the PV-Generator hybrid configuration system in each city shows different results. The City of Alor shows the most efficient yield potential for the PV-generator hybrid system because it has favorable environmental parameters. This is indicated by a high return on investment value and the lowest total Net Present Cost (NPC) condition, with a payback period for this system around 7.2 years.

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