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Techno-Economic and Environmental Analysis of an On-Grid and Off-Grid Renewable Energy Hybrid System in an Energy-Rich Rural Area: A Case in Indonesia

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Abstract—**Energy access is crucial for rural development in developing countries, as electrification drives economic growth, creates employment opportunities, and enhances the quality of life for rural communities. This study aims to determine the feasibility of powering a remote community with a hybrid energy system (HRS) combining solar photovoltaic, wind, and biogas to generate electricity and meet the energy needs of the rural area. West Waru Village was selected as the case study area due to its abundance of renewable energy sources. The HOMER tool was employed to model and optimize the HRS, providing a detailed analysis of its technical, economic, and environmental aspects. Furthermore, the study's findings were analyzed through a sensitivity analysis, considering uncertainty factors such as village load consumption, solar radiation, wind speed, and biomass availability. The best configuration for an on-grid scheme included a 2,284 kW photovoltaic (PV) system, 388 unit vertical axis wind turbine (VAWT), and a 500 kW biogas generator, resulting in a net present cost (NPC) of $8,506,090, a cost of energy (COE) of $0.054/kWh, and a payback period of 5.79 years. This configuration also reduced carbon dioxide (CO_2) emissions by 67.2% compared to grid electricity. The optimal configuration for an off-grid scheme consisted of a 5,491 kW PV system, 954 VAWT, a 500 kW biogas generator, and 4,850 batteries, with an NPC of $20,162,390 and a COE of $0.1601/kWh, reducing CO_2 emissions by 99.993%. These findings can serve as a baseline for the government to develop renewable energy systems in West Waru.**

Keywords*—*Energy-Rich Rural Area; Hybrid Energy System; Biomass; Photovoltaic; Wind Turbine.

I. INTRODUCTION

Energy plays a crucial role in rural development, particularly in developing countries [1]. Rural electrification is crucial in promoting economic growth, providing employment opportunities, and enhancing the welfare of rural residents [2], [3]. The availability of electricity has a positive impact on transforming rural areas and helping small businesses to grow [4], [5]. However, the provision of electrical energy remains predominantly reliant on fossil energy sources, which significantly contribute to environmental degradation [6]. Using fossil fuels results in air pollution from greenhouse gas emissions and contributes to global warming [7], [8]. In 2023, global CO_2 emissions reached 37.4 billion tons, an increase of 1.1% (410 million tons) from the previous year, with coal emissions accounting for over 65% of the total [9]. Therefore, sustainable energy sources have attracted attention to address the pressing climate change issue and mitigate the adverse effects of CO_2 emissions [10], [11].

Renewable energy has emerged as a promising solution to address the concerns related to climate change and environmental degradation [12], [13]. Transitioning to renewable energy sources is imperative for ensuring a sustainable future [14]. Several renewable energy sources, such as solar, wind, biomass, and marine energy, play a significant role in achieving energy transition [15], [16], [17]. Renewable energy can reduce carbon emissions and potentially bring a transformative impact on our lives in the long term [13]. According to the International Energy Agency [18], more than 80% of the emissions reductions can be achieved through electrification from renewable energy and reducing CO_2 emissions from fossil fuel operations in 2030. Although renewable energy sources have significantly contributed to emission reductions, their widespread adoption has been hindered by concerns regarding supply stability and the adequacy of technological infrastructure.

Indonesia has numerous renewable energy resources, including solar, biomass, and wind energy [19], [20]. Indonesia's tropical climate offers an excellent opportunity for the utilization of solar and wind energy potential [21][22]. Therefore, the Indonesian government issued an energy-independent village regulation, which is expected to provide villages with a minimum of 60% of their energy needs based on renewable energy [23]. West Waru Village, located in Pamekasan Regency, East Java, Indonesia, is one of the energy-rich rural areas due to its geographical conditions [24], [25]. An energy-rich rural area refers to a village with substantial renewable energy sources, such as solar, wind, and biomass, capable of meeting its own energy needs. Furthermore, West Waru village also generates a high amount of biomass from cattle farming, due to the interesting fact that each household owns a cow as livestock. However, cow manure management as potential biomass from cattle farming is often inadequate, as it is typically directly discharged into the environment [26], [27]. According to the research by [28], cow manure can be converted into biogas, which can be used to generate electricityvia biogas generator. Moreover, the high potential of various renewable resources which is available in the village can allows the development of a hybrid energy system (HRS) [29], [30]. This integration ensures the synergistic utilization of various renewable resources so that both stable and optimal energy supply can be achieved [31], [32].

HRS provides multipurpose solutions by integrating various energy sources and technologies, offering cost-effective options to meet diverse user needs [33], [34]. HRS offers a range of benefits, including increased efficiency and reduced carbon emissions, making them a promising solution for sustainable energy systems [35], [36]. They can be customized and adapted for grid connectivity and independent operation [37]. The Hybrid Optimization of Multiple Energy Resources software (HOMER) software can be employed in examining and simulating the possibilities of HRS [38]. HOMER software can simulate various power configurations, including solar PV arrays, wind turbines, generators, batteries, grids, and utility loads, providing detailed techno-economic and environmental analyses [39]. Through these simulations, it has been demonstrated that HRS can enhance energy accessibility, reduce emissions, and contribute to achieving various Sustainable Development Goals (SDGs) [40], [41], [42].

A study by [43] examined the utilization of renewable energy in Zaria Village, Nigeria which relies on gasoline or diesel generators for electricity supply. Their efforts in the energy transition are deploying solar panels, biogas, and wind turbines on HRS. The research findings revealed that the optimal HRS configuration is grid-connected of a 2000 kW solar panel, a 2500 kW biogas generator, and a 30 kW wind turbine, resulting in a renewable fraction of 95%. The study of [44] have demonstrated a techno-economic analysis by integrating multiple renewable energy sources into an off-grid HRS in the remote area of Chamarajanagar, India. This study proves the feasibility of utilizing renewable energy in a rural setting. The total daily electricity consumption in the area was 724.83 kWh/day. The research findings indicated that the PV–wind–biomass–biogas–fuel cell–battery combination scenario represented the optimal configuration, with low NPC and COE values of 890.013USD and 0.214USD/kWh, respectively. This configuration involved a 60kW biogas generator, a 50kW biomass system, a 50 kW wind turbine, a 100 kW solar panel, and a 323 kWh battery, achieving a renewable fraction of 100%. However, this HRS has not been analyzed for its connection to the grid. A study by [45] analyzed the optimum strategy for HRS technology in order to meet the electricity requirement of the rural village of Tazouta, Marocco. Detailed techno-economic optimization determined that scenario which involved a combination of biomass, wind, PV, and battery technologies, offered the most cost-effective solution. The proposed HRS with 100% renewable energy penetration would reduce 26.48 tons of CO_2 emissions annually. This significant reduction can be attributed to the system's absence of non-renewable energy sources. Despite the proposed system providing untapped opportunities, the application of standalone HRS in areas that have unstable weather raises concerns about supply stability. A renewable energy system based on micro-hydro and solar PV was developed by [46], considering rural area application in Yogyakarta, Indonesia. The analysis has been done using the HOMER tool and the extended particle swarm optimization (PSO) technique has been used to ensure optimal capacity optimization of NPC and COE. The results of this study show the combination of micro-hydro and solar PV systems can service the electrical load of 962 households. The production of electricity to supply the domestic housing load is 3273 kWh per day. Research by [47] also developed HRS by combining PV, wind, generator, and battery for residential applications in Ponorogo, East Java, Indonesia. This study reveals that systems with NPC, COE, and pollutant emissions are not always the best option. This is due to HRS development it is necessary to consider other factors including technical, economic, and environmental parameters so that the optimum choice can be executed.

Based on the existing work in the research area, both geographical conditions and the potential of renewable energy sources influence the configuration and performance of HRS. Numerous studies have recommended the HRS for both on-grid and off-grid configurations for various applications such as university campuses, public infrastructure, urban cities, and rural areas in many counties [48], [49], [50], [51]. Despite extensive research on the development of HRS across various sectors, its application in energy-rich rural areas, such as West Waru village in Indonesia, has not yet been explored. Consequently, detailed techno-economic and environmental analyses remain unexamined, and the necessary data for all stakeholders has not been provided. Hence, this study aims to fill the existing gap in the literature by developing an HRS configuration that utilizes solar, wind, and biomass energy to satisfy the energy demand in the village and simulating this configuration using HOMER software for both on-grid and off-grid scenarios. Then, the study will evaluate the techno-economic and environmental feasibility of the proposed HRS configuration. Ultimately, it aims to propose the optimal configuration by optimizing the techno-economic and environmental feasibility of the proposed HRS configuration.

A sensitivity analysis was performed to discover the effects of uncertainty factors such as village load consumption, solar radiation, wind speed, and biomass availability on the optimized renewable energy HRS. The results of this study provide essential knowledge about the practicality of HRS in serving electricity and reducing reliance on external energy supplies. In Addition, this paper offers recommendations to help policymakers develop HRS for energy-rich rural areas, supporting the goal of achieving energy-independent villages.

II. Resource Assessment of the Study Area

A. Site Description

This simulation study is located in West Waru Village, Waru Sub-district, Pamekasan Regency, East Java, Indonesia, at latitude: 06° 56' 29.8464" S and longitude: 113° 33' 11.9736" E, as presented in Fig. 1. West Waru village has an area of 8.07 km^{2,} which is 127 m above sea level. It has a population of 13,714 people with a population density of 1699.38 per km^2 [52].

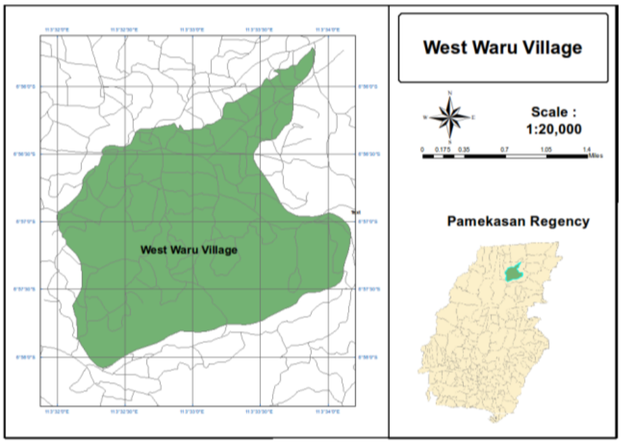


Fig. 1. The geographical position of West Waru Village [53]

B. Village Load Assessment

According to data published by BPS Pamekasan [52], 3,735 households in Waru Barat Village were using electricity supplied by State Electricity Company Indonesia (PLN). Among all the villages in the Waru Sub-district, West Waru Village had the highest number of PLN electricity consumers, exceeding the neighboring villages, which averaged fewer than 3,000 users. The monthly electricity load data for 2022 is depicted in Fig. 2(a), while Fig. 2(b) illustrates the daily 2022 electric load profile for West Waru Village. The daily load data served as the mean value obtained from household surveys at Waru Barat village. The bar chart indicates a decrease in nighttime electricity consumption, particularly from 11:00 to 03:00 am, with the highest demand between 05:00 and 09:00 pm [54]. This is a typical electrical consumption pattern in residential load, where energy demand is lower during the nighttime as people are asleep. Furthermore, when they return home to spend time with their families in the afternoon, there is a greater need for electrical energy for lighting, cooking, entertainment, and various other activities [32].

C. Resources Assessment

1) Biogas

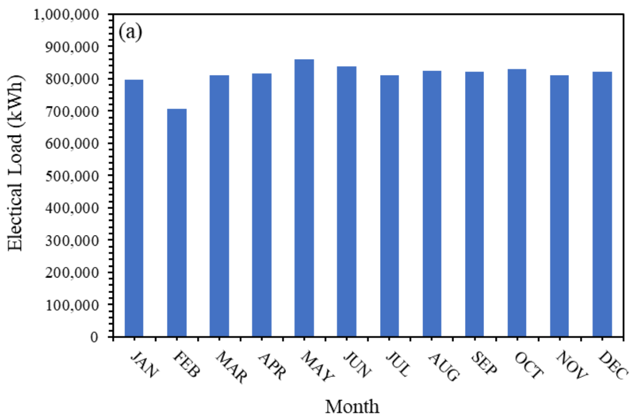
Renewable energy sources, such as biogas derived from cow dung, are widely available in the West Waru Village, with nearly every household owning several cows. Biogas can be produced from cow dung and converted into electricity through a biogas electrical generator system [5], [55]. The electricity generated has the potential to meet the current electricity demand of West Waru Village. According to research conducted by [56], an average single cow produces 15 kg of dung daily, this quantity of cow dung has the potential to generate 0.05 m3 of biogas. As identified by the [57], with a total of 3,979 cows in West Waru Village, the estimated biogas yield amounts to 2,984 m^3 per day, which can be utilized for electricity generation. A graphical representation of the projected biomass availability in West Waru Village is presented in Fig. 3 and Fig. 4 shows the number of cows in Waru Sub-districts.

2) Solar Radiation

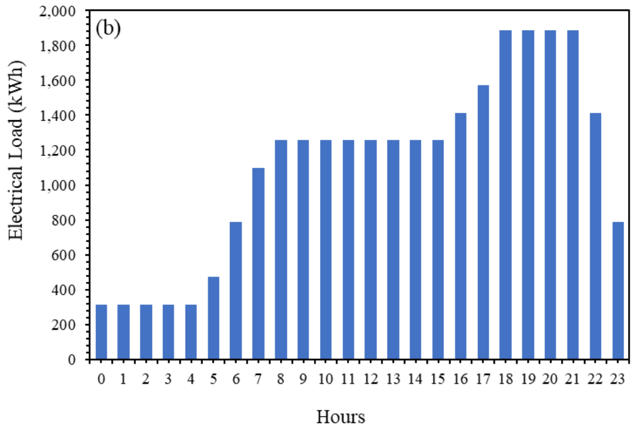
The solar radiation, clearness index, and temperature data at West Waru village were taken from the National Aeronautics and Space Administration (NASA) database [58]. The yearly average of solar radiation is 5.2 kWh/m^2/day, with the highest radiation in October and the lowest in May. Similarly, the average clearness index is 0.52, with August having the highest and November experiencing the lowest clearness index as shown in Fig. 5. The temperature data was also taken from [58] as shown in Fig. 6.

3) Wind Speed

The solar radiation, clearness index, and temperature data at West Waru village were taken from the NASA database [58]. The yearly average of solar radiation is 5.2 kWh/m^2/day, with the highest radiation in October and the lowest in May. Similarly, the average clearness index is 0.52, with August having the highest and November experiencing the lowest clearness index as shown in Fig. 5. The temperature and wind speed data were also taken from [58] as shown in Fig. 6 and Fig. 7, respectively.



(a)



(b)

Fig. 2. (a) Electrical month load profile, (b) Electrical hours load profile

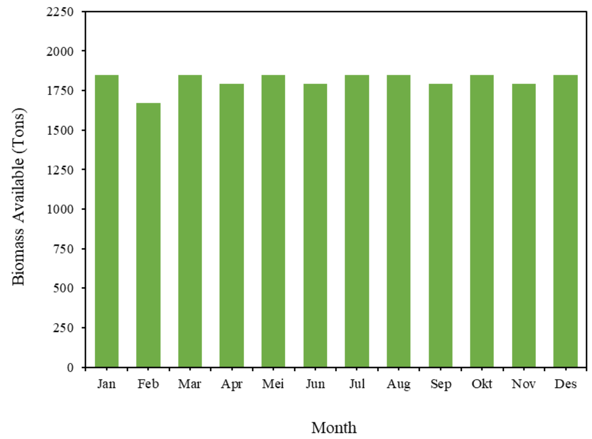


Fig. 3. Biomass availability through the year [57]

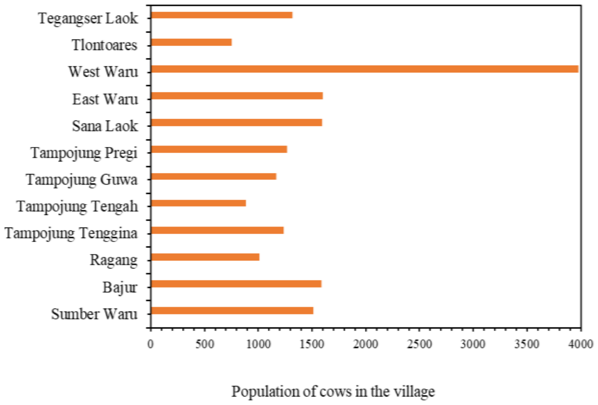


Fig. 4. Biomass potential at Waru Sub-districts, Pamekasan Regency [57]

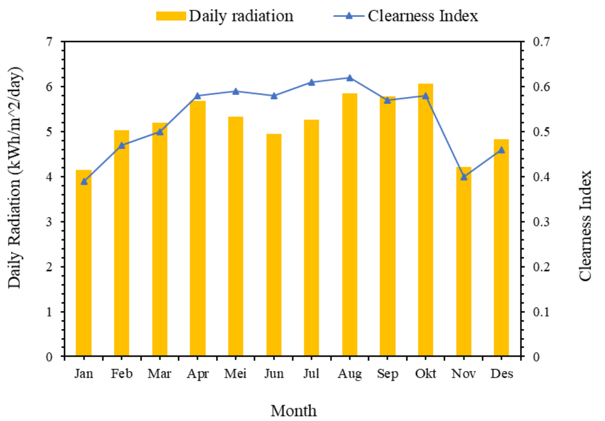


Fig. 5. Solar radiation and clearness index for the West Waru Village [58]

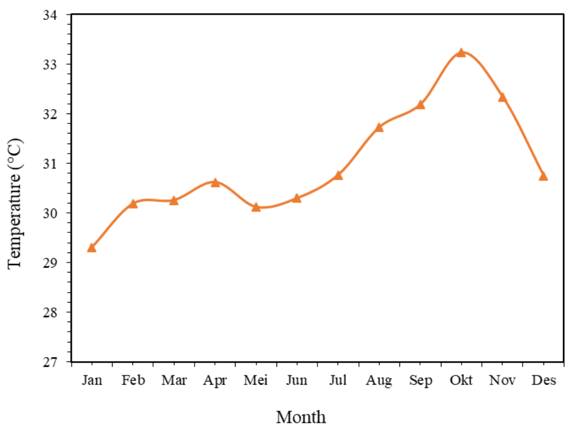


Fig. 6. Air temperature for the West Waru Village [58]

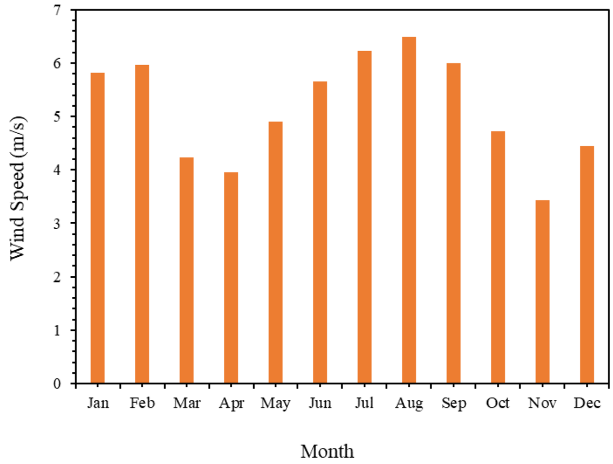


Fig. 7. The average monthly wind speed for the site at 10 m [58]

D. System Description

1) Biogas Generator

The biogas generator utilized in this study is the Energin M12 Gen B500, manufactured by Cleantech Solutions. It has a rated capacity of 500 kW, a capital cost of \$573 per kW, and a replacement cost of \$384 per kW. The generator is designed to operate for 8,000 hours over its lifetime, with a load factor of 50%, and it has access to 59.6 tons of biomass feedstock per day. The operation and maintenance costs amount to \$0.25 per hour. For every 1 kW of power generated, this biogas generator produces 0.28 grams of CO_2 and 0.025 nitrogen oxides (NO_X) [59].

2) Solar Photovoltaic

Solar energy is a viable source for generating electricity in remote areas of Indonesia where grid power is unavailable. PV arrays are the primary power source in hybrid systems. The power produced by PV arrays is directly proportional to the solar radiation available at the location [60], [61]. Longi LR6-60hpb monocrystalline PV modules were employed for this hybrid renewable design, with a capital cost of \$652 per kW and an installation cost of \$100 per kW. The PV module includes detailed technical specifications and has operational and maintenance costs of \$10 per kW. The replacement cost matches the installation cost [62]. The technical solar PV parameters are shown in Table I.

3) Wind Turbine

The wind potential availability is reasonably moderate in the Waru Barat Village area. The wind turbines utilized in this project have maximum power efficiency and a cut-in speed of 2 to 3 m/s. The study utilizes an EN-2KW-H type and using a VAWT model [63]. This model incurs capital costs of \$5,000 and operating and maintenance costs of \$10 per year. The turbine's lifespan can be extended to 25 years in HOMER, and the turbine hub can be adjusted to various heights. Fig. 8 displays the performance characteristics of this wind turbine.

4) Inverter

An inverter is an electronic device utilized in hybrid power generation to facilitate energy flow between alternating current (AC) and direct current (DC) electrical components [64], [65]. It consists of an inverter and a rectifier that converts between AC and DC and vice versa. In this study, we used Schneider Conext XW+6848 type inverters and their capital and replacement costs for a 1 kW unit, which are $500 each. The estimated lifespan of the inverter is ten years, with an efficiency of 95 % for the inverter and 95 % for the rectifier [66].

TABLE I. SOLAR PV TECHNICAL PARAMETERS [62]

Parameter	Unit	Value	
		STC	NOCT
Max Power	Pmax/W	300	222.2
Open circuit Voltage	Voc/V	39.8	37.1
Short Circuit Current	Isc/A	9.70	7.82
Voltage at Maximum Power	Vmp/V	32.9	30.4
Current at Maximum Power	Imp/A	9.13	7.32
Type	-	Monocrystalline	
Module Efficiency	%	17.9	
Operating Temperatur	°C	-40 + 85	
Temperature Coefficient ISC	% / °C	+0.057	
Temperature Coefficient Voc	% / °C	-0.286	
Temperature Coefficient Pmax	% / °C	-0.370	
Dimension	P x L x T	1683x996x35mm	
Lifetime	Year	25	

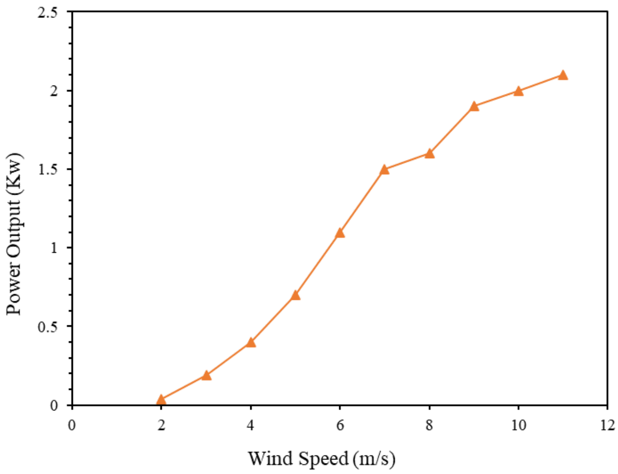


Fig. 8. Wind turbine power curve EN-2KW-H [63]

5) *Battery*

The batteries are used for backup and to maintain a consistent voltage during peak load or a power outage [67]. The battery employed in this study was 4KS25P [68]., which was attached as the central storage system at DC bus and short time intervals, making it the most popular option in hybrid systems. It has a nominal capacity of 1900Ah, a minimum SOC of 40%, and operates at 4 volts DC. The annual costs for capital, replacement, operation, and maintenance are $1,250, $1,100, and $15, respectively [68].

6) *Grid*

When the renewable energy system could not fully meet the energy demand, the grid was employed to supplement the supply. The PLN determined the grid power price to be $ 0.108 per kWh. To generate 1 kWh of electricity on the grid using a conventional fossil fuel-based power plant, it releases 865 g of carbon dioxide, 463 g of sulfur dioxide, and 226 g of NO_X [69], [70], [71].

III. METHODOLOGY

This research aims to demonstrate the viability of on-grid and off-grid solar-wind-biomass power systems in rural areas with abundant resources, explicitly focusing on Waru Barat Village in Pamekasan Regency, Indonesia, as a case study. Utilizing HOMER, the hybrid power systems are designed, and the optimal component sizes are determined through techno-economic and environmental analysis [72]. HOMER software features two optimization algorithms: the HOMER Optimizer and the original grid search method. The HOMER Optimizer uses an approach to find the system with the lowest NPC without relying on derivatives. Meanwhile, the original grid search method enhances the system by exploring all possible configurations and generating optimized lists based on NPC. Fig. 9 outlines the method used to achieve the optimal design and conduct a comprehensive techno-economic and environmental analysis of a hybrid system capable of operating both on-grid and off-grid.

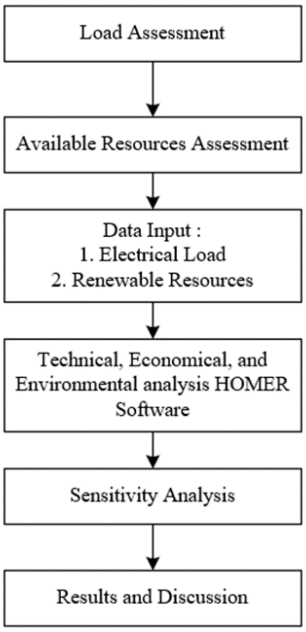


Fig. 9. Flow chart for the simulation methodology

A. *Input Data*

Meteorological data, the availability of renewable resources, load profiles, and economic and technical data are all crucial input parameters for the modeling process. Meteorological data, encompassing temperature, solar radiation, wind speed, and biomass resources, are essential for assessing the availability of renewable resources. These data are typically provided as monthly averages or time-series data. HOMER uses them to calculate the power output of PV arrays, wind turbines, and biogas generators. It is imperative to include all these data types to ensure the accuracy of the modeling process. The village's load profile for various applications is thoroughly analyzed, focusing on the area's specific requirements, which play a crucial role in power balancing calculations. Components that suit the local conditions are identified and incorporated into the model, while the cost and technical details of these components are determined. The modeling process also considers the project's lifespan and economic factors like grid expansion costs.

B. Simulation and Optimization

To propose optimal system configurations and adequately size its components, HOMER is employed to conduct system simulations and optimizations. After all the simulations, an optimization process is executed to minimize the COE and NPC for each plan. The HOMER optimizer utilizes a grid search algorithm to identify the most cost-effective system configurations. The outputs for feasible plans include component operation results for each time step and the lifetime cost associated with system installation and operation [73]. Subsequently, a list of potential plans is generated. This study uses the lowest NPC as a key optimization metric. The minimum NPC for a system is determined by aggregating all costs, including replacement costs, fuel costs, emissions penalties, operations and maintenance costs, and purchase costs [74]. Fig. 10 provides a schematic representation of the hybrid power system model in HOMER.

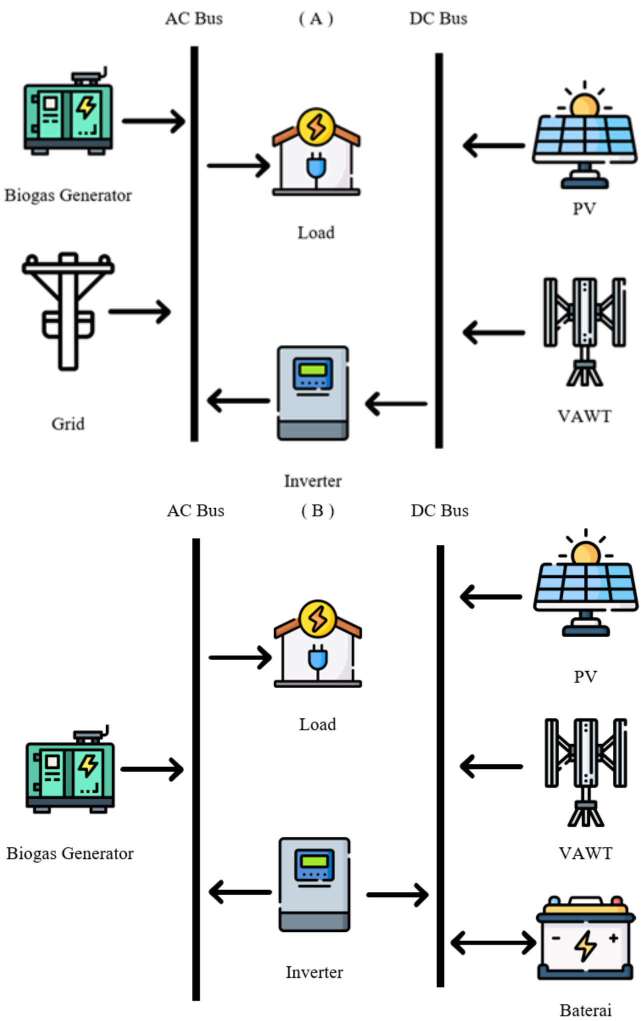


Fig. 10. Proposed configurations for two scenarios of the hybrid renewable energy system: (a) On-Grid, (b) Off-Grid

C. Technological Analysis

1) Biogas Generator

The equation for calculating the energy that biogas is capable of converting is equation (1)[71].

$$E_{BG} = \frac{Biogas\ availability\ \left(\frac{kg}{years}\right) \times CV_{BG} \times \eta BG \times \Delta t}{365 \times 860 \times h_{BG}} \tag{1}$$

CV_{BG} is the calorific value of biogas (MJ), ηBG is the efficiency biogas generator, Δt is the step time, and h_{BG} is the number of operational hours daily.

2) Solar Photovoltaic Generation

The calculation of power output (P_PV) is used to determine the power that solar panels can generate with the influence of various factors such as derating factors (dust, shadows, power loss in the network) and the influence of temperature on solar panels. The calculation of solar panel power output is presented in Equation (2) [75].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) \left[1 + \alpha_P (T_C - T_{C,STC})\right] \tag{2}$$

Where Y_{PV} is the rated capacity (kW), f_{pv} is the PV derating factor, G_T is the incident solar radiation (kW/m^2), $G_{T,STC}$ is the incident radiation under standard test conditions (STC). α_P is efficiency PV, T_c is the temperature at PV, and $T_{C,STC}$ it is the power temperature coefficient (percent /°C) under STC.

3) Wind Turbine

Wind turbines generate electricity when their blades begin to spin at speeds ranging from 2 m/s to 30 m/s, depending on the manufacturer [63]. The power output of a wind turbine can be calculated using Equation (3) [76]:

$$P_{WS} = \begin{cases} \dfrac{P_R (V_W - V_{CI})}{(V_R - V_{CI})} V_{CI} \leq V_W \leq V_R \\ P_R V_R \leq V_W \leq V_{Co} \\ 0 V_R \leq V_{CI} \text{ and } V_W \leq V_{CO} \end{cases} \tag{3}$$

Where V_R is the rated wind speed and P_R is the wind turbine's rated power output. V_{CO} and V_{CI} are the turbine's cut-out and cut-in speeds, respectively. Wind speed (V_W) can be calculated by using Equation (4):

$$V_W = V_{REF} \left(\frac{H}{H_{REF}}\right)^{\alpha} \tag{4}$$

Where H denotes the hub height of the wind turbine and is the reference velocity calculated using the reference height. α is a power law exponent that varies with the weather and wind speed. In HOMER, the turbine output power (Equation (5)) is calculated by taking into account the actual density of air (ρ) and density of air at standard pressure and temperature (ρo).

$$P_W = \left(\frac{\rho}{\rho o}\right) P_{WS} \tag{5}$$

4) Inverter

Solar panels generate DC, which may not be suitable for household applications primarily using AC. Consequently, an inverter is necessary to convert DC into AC or vice versa. Equation (6) is employed to determine the power requirements of the inverter [76].

$$P_{con} = \frac{P_L}{\eta_{inv}} \tag{6}$$

5) Battery

Given the intermittent nature of renewable energy sources, additional solutions are necessary to ensure a more consistent energy supply. One such solution is using batteries, which can store excess energy generated by renewable sources and supply it when the system cannot meet consumer demands. Equation (7) calculates the required battery capacity [71].

$$P_{bat}^{max} = \frac{N_{bat} V_{bat} I_{bat}^{max}}{1000} \tag{7}$$

D. Economic Analysis

Economic parameters such as NPC, COE, internal rate of return (IRR), return on investment (ROI), and payback period are determined for a solar-wind turbine-biomass HRS [77]. The total NPC is calculated by adding the total discounted cash flows over the project's lifetime, as shown in Equation (8) [78].

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{8}$$

Where C_{NPC} is the total NPC in dollars, $C_{ann,tot}$ is the total annualized cost in dollars per year, CRF is the capital recovery factor, i is the interest rate in percentage (8%), and R_{proj} is the project lifetime in years [37]. The CRF is calculated using the Equation (9).

$$CRF = \frac{i(1+i)^{Rproj}}{(1+i)^{Rproj} - 1} \tag{9}$$

The total cost per useful kilowatt of electrical energy produced is defined as COE [79], and it is calculated using Equation (10).

$$COE = \frac{C_{tot}}{E_r} \tag{10}$$

C_{tot} is the total cost of all systems over the project's lifetime in dollars per year, and E_r is the total energy served in kilowatt-hours per year

E. Environmental Analysis

The environmental analysis considers the emissions produced by the electricity grid and the biogas generator. The emissions per 1 kWh, as described in the system descriptions, are used for this assessment.

F. Sensitivity Analysis

In the study by Pujari & Rudramoorthy, (2022), sensitivity analysis is employed to assess the impact of uncontrollable variables, including solar radiation, wind speed, biomass availability, and load [80]. This analysis involves modifying input values and economic parameters within a specified range. The primary goal of sensitivity analysis is to identify the optimal values of specific variables used in designing renewable energy configurations with hybrid systems [81]. Moreover, it provides valuable insights during the optimization process regarding how the outcomes of technical and economic evaluations vary based on input values [82]. The analysis also considers future load growth, recognizing that the load profile may change over the project's lifespan due to increased electrical equipment usage by different users. For instance, villagers might adopt electric ovens and washing machines or require more electricity for modern agriculture, small commercial, and industrial activities. As a result, the load demand is expected to increase by 20% from the initial load, reflecting local development conditions or fluctuations in electricity load. In the context of hybrid systems, the analysis accounts for uncertainties in renewable energy resources such as solar radiation, wind speeds, and biomass availability, which may vary within a certain range from year to year. The values used for sensitivity analysis are detailed in Table II.

TABLE II. SENSITIVITY VARIABLES

Variations	Variable Sensitivity	Unit	Value
-20%	Electricity Consumption	kWh/day	21,362
-10%			24,033
0%			26,704
10%			29,373
20%			32,044
-20%	Solar Radiation	kWh/m^2/day	4.16
-10%			4.68
0%			5.20
10%			5.72
20%			6.24
-20%	Wind Speed	m/s	4.748
-10%			5.716
0%			5.685
10%			6.653
20%			7.622
-20%	Biomass Availability	Tons/day	47.748
-10%			53.716
0%			59.6
10%			65.653
20%			71.622

IV. RESULTS AND DISCUSSION

A. System Optimization Results

1) On-Grid

The most efficient hybrid configuration for the grid-connected microgrid system combines various energy sources: a 500 kW biogas generator, a 2,284 kW PV array, a 388 kW wind turbine, and a 1,501 kW system converter. This setup offers impressive economic benefits, with an NPC of \$8,506,090.00 and a COE of \$0.0544 per kilowatt-hour, which is cheaper than reported by [56]. It also boasts a renewable fraction of 79.20%, indicating a strong reliance on renewable energy. This proposed on-grid system can reliably meet the entire energy demand of the village (Table III). Any surplus energy produced can be fed back into the grid using a net metering system, as supported by [83]. In comparison, the Wind/BG/Grid configuration, while producing more renewable energy (4,812,403 kWh/year), results in a higher NPC ($11,205,580.00) and COE ($0.0823), and it produces more CO_2 emissions (2,560,602 kg/year). The PV/BG/Grid configuration is slightly cheaper with a COE of $0.0518 but has a lower renewable fraction (75.50%) and higher initial capital cost ($4,784,870.75). Additionally, the proposed system excels economically, with an IRR of 16.10% and a ROI of 12.10%, coupled with a shorter payback period of 5.79 years. Environmentally, it is beneficial with lower CO_2 emissions (2,177,817 kg/year) compared to other configurations. These metrics collectively indicate that the proposed system is the most efficient and economically viable option for meeting the village's energy needs.

2) Off-Grid

The optimal off-grid microgrid system, as shown in Table IV, combines PV, wind, and biomass generation with a battery storage system. This setup includes a 500-kW biogas generator, a 5,491 kW PV array, a 954 kW wind turbine, a 2,656 kW system converter, and 4,850 batteries with a capacity of 1900 Ah each. Economically, this configuration has an NPC of $20,162,390.00 and a COE of $0.1601 per kilowatt-hour, which is cheaper than the findings of [84], [85], [86]. However, it requires a higher initial investment of $15,933,626.34, and its NPC and COE are higher than those of the on-grid configuration. Comparing different off-grid configurations, the PV/BG/Bat setup, with a higher initial capital of $18,615,507.18 and an NPC of $25,098,108.94, has a COE of $0.1994, which is more expensive than the PV/wind/BG/Bat setup but still offers 100% renewable energy. The Wind/BG/Bat configuration, with the highest initial capital ($25,774,062.36) and NPC ($30,552,366.64), has the highest COE at $0.2426. Despite its substantial initial investment, the PV/wind/BG/Bat configuration is the most cost-effective among the off-grid options. In this off-grid system, all energy comes from renewable sources. The biogas, PV, and wind units reliably meet the village's energy demand year-round. Monthly, the biogas generator contributes about 12.0% of the total power, the wind turbine about 39.2%, and the PV array about 48.8%. The higher contributions from the PV array and wind turbine are due to better solar radiation and wind speed, as well as the limited capacity of the biogas generator, as noted by [87]. These contributions are depicted in Fig. 12, which shows the monthly distribution of power generation from different sources. In contrast, while the on-grid system is cheaper in terms of NPC and COE, it partially relies on non-renewable sources, leading to emissions. The off-grid system, entirely reliant on renewables, has a significant environmental advantage, producing only 535 kg/year of CO_2 and 0.07 kg/year of NO_X for the PV/wind/BG/Bat setup, compared to higher emissions in on-grid configurations.

3) Sensitivity Analysis Results

The simulation results of the On-Grid configuration show a COE value of $0.0544 per kilowatt-hour, which is lower than the electricity price provided by the PLN at $0.108 per kilowatt-hour. This comparison contrasts with the Off-Grid scenario with a COE of $0.1601 per kilowatt-hour. Hence, the off-grid configuration is unsuitable for implementation in the village of Waru Barat due to its higher cost than the on-grid scenario. Therefore, this configuration is considered feasible and recommended. To assess the proposed electrical system's capability to handle load demand and renewable energy availability uncertainties, variations were introduced in electric load, solar radiation, wind speed, and biomass availability with an uncertainty level of ±20%. Based on the graph in Fig. 13, it can be observed that there is an increase in electricity production for each system. Solar panel experiences a significant increase compared to wind turbines and biogas generators in electricity production, this result was also found in the research by [88].

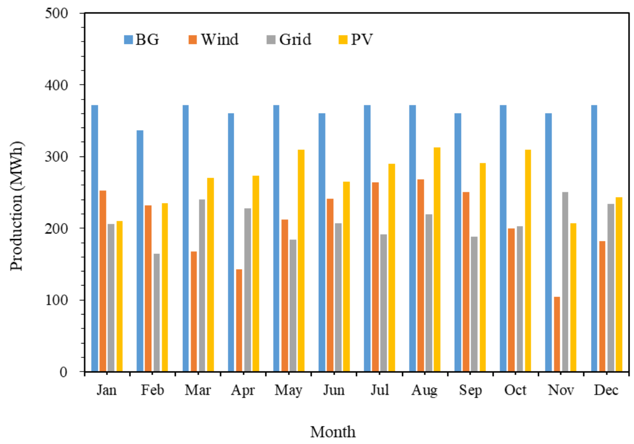


Fig. 11. Power output of the generating PV/Wind/BG/Grid throughout the year

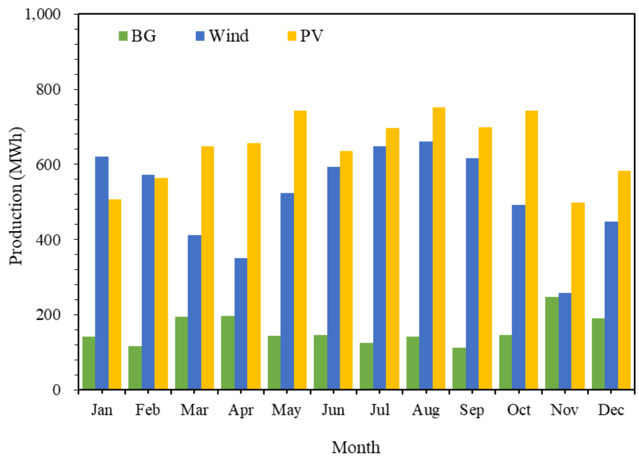


Fig. 12. Power output of the generating PV/Wind/BG/Battery throughout the year

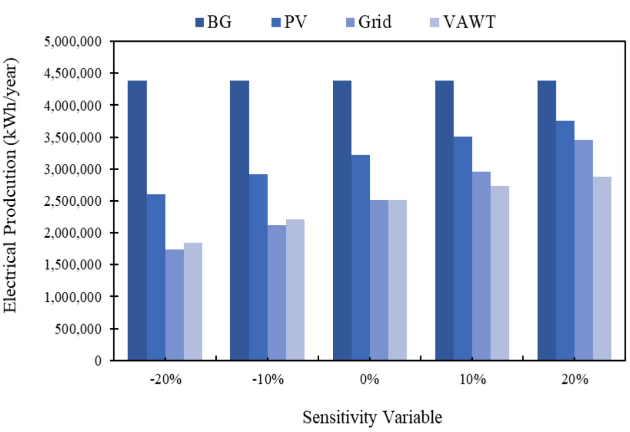


Fig. 13. Effect of scaled sensitivity variables on Electricity Production

TABLE III. ON-GRID SIMULATION RESULTS

Item	Unit	PV/Wind/BG/grid	PV/BG/Grid	Wind/BG/Grid
PV	kW	2,284	4,451	
Wind	Unit	388		742
BG	kW	500	500	500
Converter	kW	1,501	2,191	1,252
Renewable Fraction	%	79.20	75.50	71.90
PV Production	kWh/year	3,216,440.00	6,267,507.00	
Wind Production	kWh/year	2,516,459.00		4,812,403.00
BG production	kWh/year	4,380,000.00	4,380,000.00	3,082,000.00
Total Production	kWh/year	12,629,183.00	13,842,428.00	10,853,636.00
Excess Electricity	kWh/year	279,517.00	516,202.00	90,802.00
Grid sales	kWh/year	2,335,856.00	3,297,817.00	784,881.00
Initial Capital	$	4,750,353.60	4,784,870.75	4,678,125.00
NPC	$	8,506,090.00	8,731,922.00	11,205,580.00
COE	$/KWh	0.0544	0.0518	0.0823
IRR	%	16.10	15.70	11.10
ROI	%	12.10	11.70	7.80
Payback Period	years	5.79	5.79	8.01
Carbon dioxide	kg/year	2,177,817.00	2,764,836.00	2,560,602.00
Sulfur Dioxide	kg/year	1,165,040.00	1,479,248.00	1,370,125.00
Nitrogen Oxide	kg/year	312,019.00	396,170.00	366,945.00

TABLE IV. OFF-GRID SIMULATIONS RESULTS

Item	Unit	PV/wind/BG/Bat	PV/BG/Bat	Wind/BG/bat
PV	kW	5,491	10,966	-
Wind	Unit	954		2,825
BG	kW	500	500	500
Converter	kW	2,656	3,606	2,958
Battery	Unit	4,850	7,436	8,886
Renewable Fraction	%	100.00	100.00	100.00
PV Production	kWh/year	7,729,749.00	15,436,574.00	-
Wind Production	kWh/year	6,199,276.00		18,844,902.00
BG production	kWh/year	1,904,000.00	2,887,000.00	1,491,500.00
Total Production	kWh/year	15,833,026.00	18,323,574.00	20,336,402.00
Excess Electricity	kWh/year	5,281,649.00	7,455,059.00	9,829,472.00
Initial Capital	$	15,933,626.34	18,615,507.18	25,774,062.36
NPC	$	20,162,390.00	25,098,108.94	30,552,366.64
COE	$/KWh	0.1601	0.1994	0.2426
Carbon dioxide	kg/year	535.00	811.00	419.00
Nitrogen Oxide	kg/year	0.07	0.11	0.06

Fig. 14 and Fig. 15 illustrate the impact of sensitivity variations on renewable energy fractions, excess energy, and key economic indicators. Fig. 14 shows that as sensitivity variations increase, the renewable fraction decreases while excess energy rises. This indicates a reduced penetration of renewable energy due to the rising electrical load, which renewable sources cannot entirely meet, leading the conventional power grid to fulfill these higher energy demands, as supported by [89], [90]. Fig. 15 highlights the results of a sensitivity analysis on economic indicators, revealing that the COE increases with both upward and downward variations in sensitivity variables, while the NPC value rises as sensitivity variables increase due to escalating operational costs. This underscores the importance of sensitivity analysis in understanding how uncertainties impact economic outcomes.

Fig. 16 illustrates how emissions increase as parameter variations rise. This is due to the growing electricity demand, which boosts emissions in the system configuration. The decline in renewable energy penetration, as seen in Fig. 14, contributes to this trend. Essentially, increasing parameter variations have two contrasting effects. On one hand, higher electricity demand can reduce emissions by incorporating more renewable energy sources and sustainable processes. On the other hand, the decrease in renewable energy penetration leads to a greater reliance on conventional energy sources, which are more environmentally polluting. This highlights the complex interplay between energy demand, renewable energy use, and emissions in the system [32].

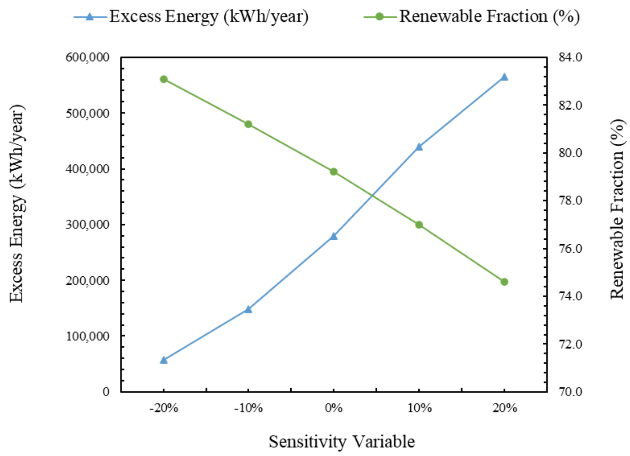


Fig. 14. Effect of scaled sensitivity variables on renewable fraction and excess energy

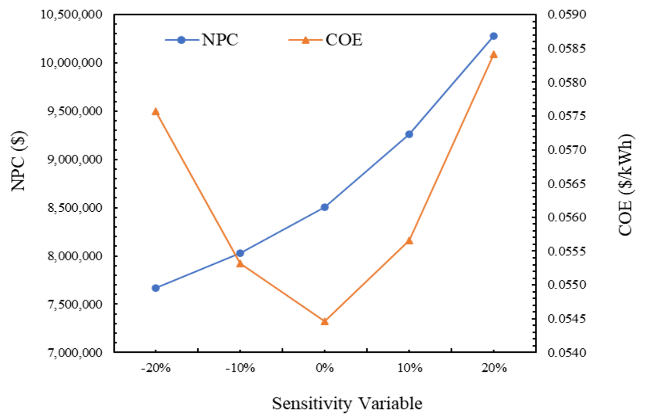


Fig. 15. Effect of scaled sensitivity variables on NPC and COE

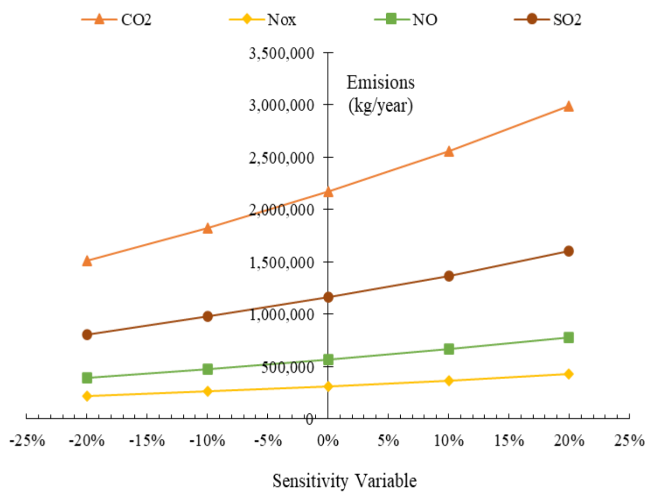


Fig. 16. Effect of scaled sensitivity variables on Emissions

4) *Effect of variation in scaled annual village load*

The estimated domestic load demand is 26,703 kWh per day. Because load demand is dynamic, the variation in domestic load is considered, ranging from 21,362 to 32.043 kWh/day. As a result, the NPC rises from $ 6,981,547 to $ 11,098,500, while the COE rises from $ 0.0488 to $ 0.0646 /kWh as load demand rises, because electricity production from the grid is increased as studied by [91] as shown in Fig. 17.

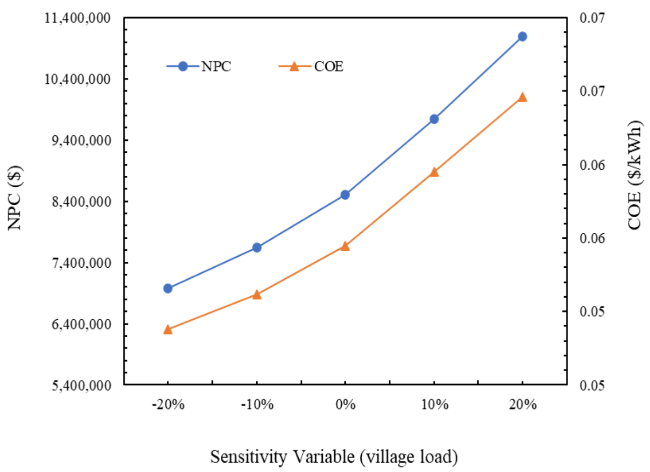


Fig. 17. Variation of NPC and COE with village load

5) *Effect of variation in scaled annual solar average*

At the study site, the average solar radiation is 5.2 kWh/m2/day. By holding all other parameters constant, the radiation at the site is varied from 4.16 to 6.24 kWh/m2/day. Fig. 18 depicts the corresponding variations in NPC and COE. As the intensity of solar radiation increases, so does the output power of the solar system, resulting in a decrease in NPC from $8,968,896 to $8,226,836 and a decrease in COE from $0.0589 to $0.0517 as studied by [71], because PV array can produce more electricity when solar radiation is increased and production from the grid is decreased.

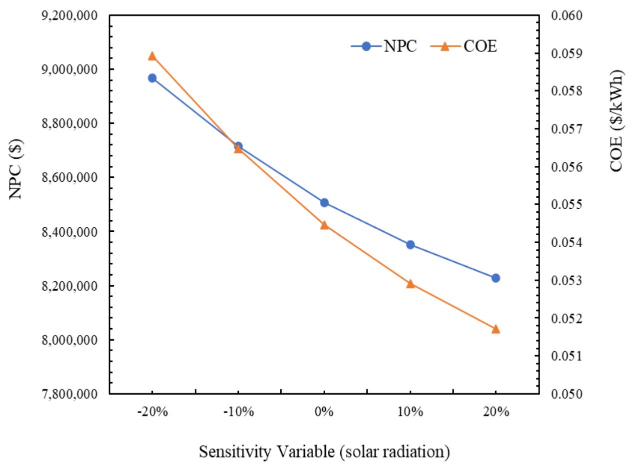


Fig. 18. Variation of NPC and COE with solar radiation

6) *Effect of variation in scaled annual windspeed*

At the study site, the average wind speed is 5.1 meters per second (m/s). The wind speed at the site varied from 4.1 to 6.1 m/s by holding all other parameters constant. Fig. 19 depicts the corresponding variations in NPC and COE. With an increase in windspeed intensity, the output power of the wind energy system increases, resulting in a decrease in NPC from $ 9,166,031 to $ 8,171,609 and a decrease in COE from $ 0.0603 to $ 0.0515, which is due to a reduction in the number of units of the total wind turbine so that the Electricity load can be met, this is supported research by [84].

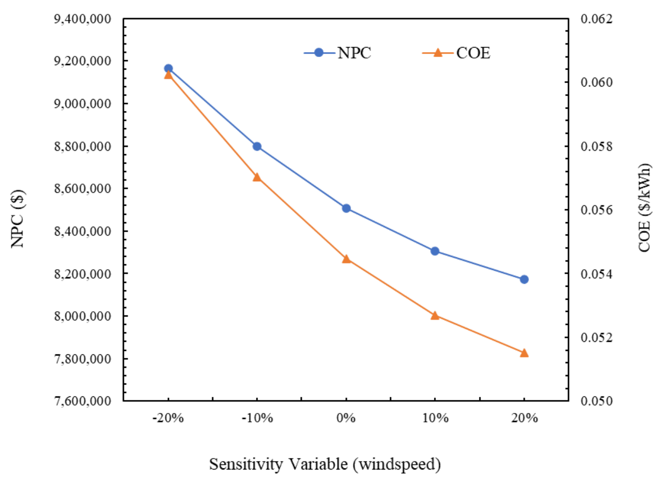


Fig. 19. Variation of NPC and COE with wind speed

7) *Effect of variation in scaled annual biomass availability*

The study site has an average biomass availability of 59.6 tons per day. Keeping all other parameters constant, the biomass availability at the site ranges from 47.74 to 71.62 tons per day. Notably, no discernible impact on NPC or COE remains stable with no decrease or increase because, with the minimum amount of biomass availability, the system is still able to supply the biogas needs of the biogas generator. Fig. 20 depicts this, with variations in NPC and renewable fractions exhibiting consistency. The output power of the biomass energy system remains constant as biomass availability changes, resulting in a consistent NPC of $ 8,506,080 and a consistent COE of $ 0.0545 across the range, which is the same result found by [92].

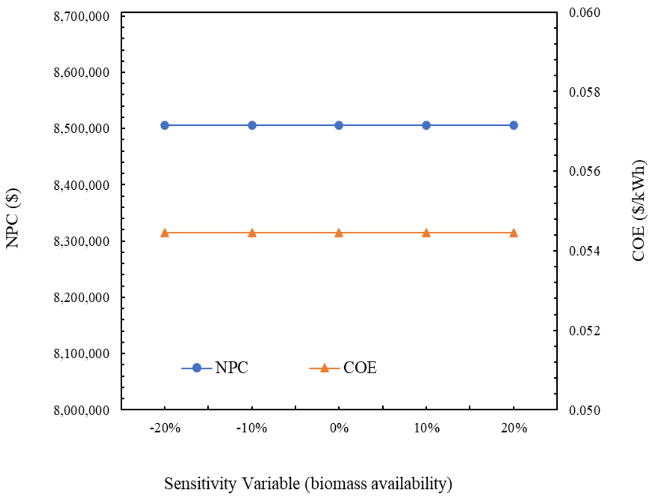


Fig. 20. Variation of NPC and COE with biomass availability

V. Conclusion

This study conducted a comprehensive techno-economic and environmental analysis of a hybrid renewable energy system in West Waru Village, Indonesia, utilizing HOMER software for optimization. The analysis compared on-grid and off-grid configurations, integrating solar PV, wind, and biogas energy sources. For the on-grid configuration, the optimal setup included a 2,284 kW PV system, 388 wind turbines, and a 500 kW biogas generator. This configuration resulted in an NPC of $8,506,090, a COE of $0.054/kWh, and a significant reduction in CO_2 emissions by 67.2% compared to traditional grid electricity. This system proved to be both economically viable and environmentally beneficial, demonstrating a payback period of 5.79 years. The off-grid configuration, incorporating a 5,491 kW PV system, 954 wind turbines, a 500 kW biogas generator, and 4,850 batteries, achieved a higher NPC of $20,162,390 and a COE of $0.1601/kWh. Despite its higher initial costs, this setup offered a remarkable 99.993% reduction in CO_2 emissions, showcasing its potential for significant environmental impact. However, the higher COE and NPC make this configuration less economically attractive compared to the on-grid alternative. Sensitivity analysis revealed that variations in load consumption, solar radiation, wind speed, and biomass availability significantly influence the system's performance and economic feasibility. The on-grid system consistently proved to be the most cost-effective and reliable option for West Waru Village, capable of providing a stable energy supply while reducing greenhouse gas emissions. This study highlights the feasibility and benefits of deploying hybrid renewable energy systems in energy-rich rural areas. The findings provide a valuable baseline for policymakers and stakeholders to develop sustainable energy solutions in similar regions. Implementing such systems can drive rural development, reduce reliance on fossil fuels, and contribute to global efforts to mitigate climate change. The model developed in this paper is based on an HRS using solar PV, wind turbines, and a biogas generator fueled by cow manure. Future models can be expanded to incorporate other biomass sources, such as agricultural residues from rice, corn, and other crops. This work can be further extended with a new integrated model to solve distribution planning issues by implementing renewable energy resources as an attractive option in distribution utility systems.

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