Optimization Sizing of 100% Hybrid Renewable Energy and Battery Sensitivity Analysis

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Abstract. Using renewable energy power plants is a strategic approach to mitigating global warming, which poses a threat to life worldwide. The design of a 100% renewable hybrid energy system must be carefully optimized to ensure system efficiency and cost-effectiveness. The primary objectives of the optimization in this article are to minimize both the overall system cost and the cost of energy (COE). The renewable energy sources considered include solar PV, wind turbines, biodiesel generators, and batteries for energy storage. As a case study, the electricity system of the Nusa Penida Islands in Klungkung Regency, Bali, was analyzed. Key inputs for the HOMER software included daily electricity load characteristics, solar irradiation data, and wind speed data for the Nusa Penida area, which were used to determine the optimal sizing of the renewable energy plants. A sensitivity analysis was performed for four types of batteries (ZB, FB 333, 1 MLI, and NaS), with the state of charge (SOC) and battery lifetime as the key variables. The simulation results indicated that solar PV was dominant in achieving the lowest COE. The sensitivity analysis further revealed that a lower SOC percentage and longer battery lifetime contributed to a reduction in COE.

Keywords: HOMER, Optimization, Renewable Energy, Sensitivity Analysis

1 Introduction

Increasing global warming has become a world issue threatening human life and the environment. Efforts have been made to limit carbon emission production to prevent this issue from increasing. The biggest contributor to carbon emissions comes from electricity generation using fossil fuels. It is reported that fossil fuel-powered generating facilities contribute approximately 43% of CO2 emissions worldwide (Babatunde et al., 2020). In Indonesia, generating facilities contributed 34% of the 1,334 million tonnes of CO2e, and in Bali contributed 41% (4,197 Gg CO2e) of the 10,377 Gg CO2e. Renewable energy (RE) is a form of sustainable energy that is being developed as a clean and green future energy source. As an energy source, the advantages of RE are that it is low carbon, has a lower impact on the environment, and

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is more promising for meeting current and future electricity needs (Kumar & Deokar, 2018). Using RE will reduce emissions caused by the electricity industry (Babatunde et al., 2020). Increasing the use of RE and radical transformation of the global energy system is one way to mitigate the threat of global climate change (Bogdanov et al., 2021). During the implementation of the RE system, one of the most critical problems is determining the optimal system sizing to produce reliable system performance and low economic value. Various optimization methods in renewable energy hybrid systems have been widely explored in research, including HOMER (Hybrid Optimization Model for Electric Renewable) (Alonso et al., 2024), Golged Jackal Optimization (GJO) (R. P. Kumar & Karthikeyan, 2024), as well as hybrid approaches using HOMER Pro, Python, Fire Hawk Optimizer (FHO), Gray Wolf Optimizer (GWO), and Particle Swarm Optimization (PSO) (Pamuk, 2024). Other techniques include differential evolution (DE) (Kamal et al., 2023), the multi-objective artificial hummingbird optimizer (MOAHA) (Yousri et al., 2023), and a complete mathematical model of hybrid systems (Nasser & Hassan, 2023). With the particle swarm optimization (PSO) algorithm has been featured in several studies (Javed et al., 2021).

Solar PV and wind turbines, as renewable energy (RE) sources, exhibit stochastic characteristics, necessitating a storage system to maintain the stability of a 100% RE hybrid microgrid. Research on storage systems has garnered significant attention, with discussions ranging from various energy storage technologies and battery types to compressed air energy storage, flywheel energy storage, and electrical energy storage solutions like supercapacitors and superconducting magnetic energy storage, as well as thermal and hybrid systems (Jiao & Månsson, 2023). The use of lithium-ion batteries in 100% RE hybrid microgrids has also been explored (Ennemiri et al., 2024), alongside hydrogen storage systems (Nasser & Hassan, 2023). Batteries are widely applied in 100% RE microgrids as flexible energy storage solutions. Therefore, this article compares the economic value of four battery types (Li-ion, VRLA, Na-S, and Lead Acid) in a hybrid system using HOMER software. In a microgrid system with the same electrical load and identical RE generator size, an experiment using the HOMER software was conducted by varying the type of battery employed. The outcomes of the battery substitution were compared in terms of energy costs, investment costs, and the lifespan of each battery type. This article presents the optimization of electricity generation in a 100% renewable energy hybrid microgrid system consisting of solar PV, wind turbines, and a biodiesel generator integrated with a battery storage system. The system is implemented for the well-known tourist destination of Nusa Penida in Klungkung Regency, Bali Province.

1.1 100% Renewable Energy Microgrid System

The microgrid system consists of solar PV, wind turbines, energy storage batteries, inverters, biodiesel generators, and electrical loads. When the electric power generation from solar PV and wind turbines is greater than the load requirement, the excess power generation produced will be used to charge the battery. Battery charging will stop when the battery's SOC (state of charge) has reached maximum capacity. When generating electrical power from diesel PV and wind turbines, which are smaller than the load requirements, the battery will discharge power (discharging) to meet these needs. When the battery continues to supply electrical power to the load and its depth of discharge (DoD) approaches the minimum threshold, the biodiesel generator (serving as a backup power source) will automatically activate. It will then generate power and distribute it to the load, ensuring continuous power supply and preventing the battery from reaching critically low levels. Frame Work Homer Optimization. HOMER (Hybrid Optimization of Multiple Energy Resources) software helps navigate the complexities of designing cost-effective and reliable hybrid microgrid and grid-connected systems. It integrates traditionally generated power, renewable energy sources, storage, and load management. With over 250,000 users across 193 countries, HOMER has become a critical tool for system optimization.

2 Methodology

The optimization framework with Homer consists of three different stages. The first stage is to create a conceptual design for a 100% renewable energy hybrid system architecture. Then, in the HOMER software, the location for placing the hybrid system is selected and introduced to the electricity load data (Figure 3), meteorological data for the area (Figure 4, 5 and 6), and technical characteristics and economic data of the various components used (Table 1, 2). In the second stage, HOMER performs optimization by generating a group of hybrid system sizing options demonstrating NPC and COE minimization within certain limits. In the third stage, four types of batteries with their respective characteristics are entered into the HOMER system, and the results are compared in terms of technical, economic, and environmental parameters to select the optimal battery option.

2.1 Load Profile and Meteorological Data Nusa Penida Island

A case study in this research is the Nusa Penida Islands area (8041.6'S, 115031.2' E) in Klungkung Regency, Bali Province, Indonesia. The Nusa Penida Islands consist of three inhabited islands: Nusa Penida Island, Lembongan Island, and Ceningan Island. They have an area of around 210 km2, the highest elevation is 524 meters, and the population was 59,500 in 2022.

Load Profile. With the development of Nusa Penida as a tourist destination, the electricity load group in Nusa Penida is dominated by the business category 61%, the housing category 30%, social 5%, industry 3%, and others 1%, where the housing category is the largest. The highest electricity load recorded in Nusa Penida has reached 12.2 MW. The daily characteristic profile is shown in Figure 1. The average daily load during the day and night is similar.

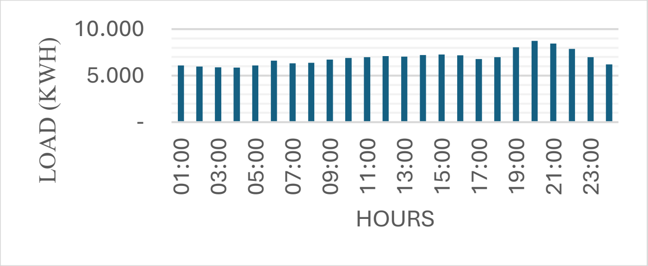

Figure 1. Daily load profile

Meteorological Data. Using the Homer software for the Nusa Penida area, the monthly average for global horizontal radiation over 22-year period (July 1983 – Jun 2005) is shown in Figure 2, with an average value of 5,340 kWh/m2/day. The lowest value was 5,040 kWh/m2/day in February, and the highest value was 6,190 kWh/m2/day in October.

Figure 2. Solar irradiance of selected area Nusa Penida

The monthly ambient temperature over 30 years (January 1984 – December 2013) is shown in Figure 3, with an average value of 26.65 ^{0}C. The lowest value was 251.42 ^{0}C in August, and the highest value was 27.42 in November.

Figure 3. Ambient temperature of selected area Nusa Penida

From NASA's prediction of the worldwide Energy Resource (POWER) database, the monthly average wind speed at 50 m above the earth's surface over 30 years (January

1984 – December 2013) is shown in Figure 4, with an average value of 4.25 m/s. The lowest value was 3.23 m/s in March, and the highest was 5.35 m2/s in July.

Figure 4. Wind speed of selected area Nusa Penida

Table 1. Technical characteristics of hardware components

Component	Characteristics	Value
PV Module /Canadian Solar Max-CS6U-330	Nominal max power (Pmax)	330 W
	NOCT	$45 \pm 2\ ^0C$
	Module efficiency	16,97%
	Opt. operating voltage	37.2V
	Opt. operating current	8.88 A
	Open-circuit voltage	45.6 V
	Short-circuit current	9.45A
	Power temperature coefficient	− 0.41%/°C
Wind Turbin / AWS650	Rated output	650 W
	Rated wind speed m/s/mph	10,5 / 24
	Peak output	750 W
	Rated current (Impp)	5.98 A
	Cut in m/s/ mph	2.7 / 6
	RPM-50hz/60hz	600 / 750
	Monthly KWH 10mph / 4,5 m/s PLF %	72 kWh (18%)
	Monthly KWH 10mph / 4,5 m/s PLF %	161kWh (25%)
Diesel generator (Type 1)	Rated capacity (RD	50 kW
	Fuel curve intercept coefficient	1.65 L/h
	Fuel curve slope	0.267 L/h/kW
Converter / Sinexcel PWG-100	Nominal power	100 kVA
	Battery voltage range	250-520V
	Batter DC max current	300A
	PV voltage range	520-900V
	PV DC max current	384A
	AC voltage	423-528V
	AC current	120A

Table 2. Technical characteristics type of batteries

Characteristics	Type of batteries			
	Idealized battery model-generic 1kWh zinc bromide flow battery (ZB)	Idealized battery model FB 333-4hours (FB 333)	Idealized battery model-generic 1MWh Li-Ion (1MLI)	Idealized battery model - NaS battery (NaS)
Nominal capacity (kWh)	1,000	1,330	1,000	1,450
Nominal capacity (Ah)	1,670	1,330	1,670	7,550
Nominal voltage (V)	600	1000	600	192
Round-trip efficiency	90%	75%	90%	85%
Max. charging current (A)	1,670	333	1,670	1,200
Max. discharge Current (A)	5,000	333	5,000	1,410
Minimum state of charge	20%	20%	20%	20%
Min Lifetime	5	5	5	5

Table 3. Economic characteristics of hardware components

Component	Capital ($)	Replacement ($)	O&M
CS6U-330P	1,079.77	37.49	62.24 ($/year)
AWS650	2,798	892.02	517.10 ($/year)
Bio	3,000	1.250	0.10 ($/op.hr)
Sinexcel PWG-110	50,000	30,000	1,500 ($/year)
ZB	400	400	10 ($/year)
FB 333	1,119,492	0	0
1MLI	700,000	700,000	10,000 ($/year)
NaS	380,000	380,000	5,000 ($/year)

2.2 Modelling System

Simulation with HOMER software for a 100% RE system consisting of solar PV, wind turbine, biodiesel, inverter, and the battery is carried out by alternately entering four types of battery technical and economic characteristics, namely NaS, ZBF, Li-On, and FB 333 (Table 2). Meanwhile, the characteristics of the components of solar PV, wind turbines, bio generators, inverters, and the electrical load are maintained constant. Calculations are continued to obtain the best performance from each battery, and a sensitivity analysis is carried out by entering changes in the values of two variables influencing the battery: the variable lifetime (years) and minimum state of charge. The variable lifetime (years) is 10, 15, 20, and 25 years. Meanwhile, for the minimum battery state of charge (%) variable, the values 20, 30, 40, and 50 are chosen. Meanwhile, the initial state of charge (%) and minimum storage life (yrs) variables are fixed with the values 100 and 5, respectively.

3 Result and Discussion

3.1 Result

After inputting data on each component's technical and economic characteristics according to the data in Tables 1 and 2, the HOMER software will display the 100% RE system architecture as in Figure 5. The same sensitivity variable is input for each type of battery. Next, optimization calculations are carried out to obtain the lowest NPC value. The optimization winner and sensitivity analysis are shown in the following discussion.

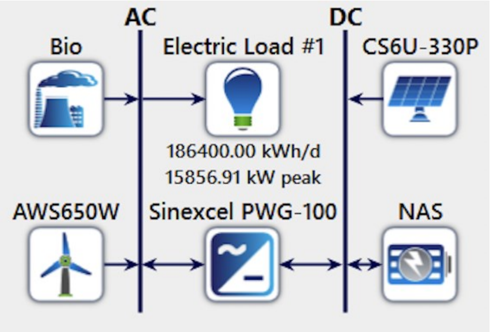

Figure 5. Schematic system 100% RE

Optimizing for Lowest Net Present Cost. With input solar PV type SC6U-330P, wind turbine type AWS650, bio generator 500 kW, inverter Sinexcel PWG-100, and four types of batteries ZB, NaS, FB 333, and 1 MLI, they are resulting in an architecture with a different base case for each battery type as shown in table 3. When input using a ZB battery, the winner of the optimization with the lowest NPC value is the base case with the composition SC6U-330P with a capacity of 50,999 kW, ZB with 1,068 units, and Sinexcel PWG-100 with a total capacity of 14,860 kW, lifetime ten years and minimum SOC 20% with NPC $ 111M, Operation cost $ 3.7M, COE $ 0.1236. Electrical power production is 81,399,650 kWh/yr, and power consumption is 68,014,824 kWh/yr. For input using a NaS battery, the winner of the optimization with the lowest NPC value is the base case with the composition SC6U-330P with a capacity of 101,339 kW, NaS with a total of 276 units and Sinexcel PWG-100 with a total capacity of 16,767 kW, a lifetime of 10 years and a minimum SOC of 20 % with NPC $386M, Operation cost $13M, COE $ 0.4389. Electrical power production is 161,749,825 kWh/yr, and power consumption is 68,014,824 kWh/yr. When input using the FB 333 battery, the winner of the optimization with the lowest NPC value is the base case with a composition of Bio-500 kW, SC6U-330P with a capacity of 116,078 kW, FB 333 with a total of 260 units and Sinexcel PWG-100 with a total capacity of 16,670 kW, lifetime ten years and minimum SOC 20% with NPC $ 526M, Operation cost $ 7.7M, COE $ 0.5991. Electrical power production is 185,280,206 kWh/yr, and power consumption is 67,989,459 kWh/yr. When input using a 1MLI battery, the winner of the optimization with the lowest NPC value is the base case with the composition SC6U-330P with a capacity of 163,949 kW, 1MLI with a total of 235 units and Sinexcel PWG-100 with a total capacity of 16,644 kW, a lifetime of 10 years and a minimum SOC of 20 % with NPC $644M, Operation cost $22.83M, COE $0.733. Electrical power production is 261,682,334 kWh/yr, and power consumption is 67,989,401 kWh/yr.

Table 4. Comparison between optimization winners for each type of battery

Architecture 100% RE					Economy			Electrical		
Type of battery	Unit of battery	Solar PV-CS6U-330P (kW)	Bio generator 500 KW (unit)	Inverter - sin-excel PWG-100 (kW)	NPC ($)	Operation ($)	COE (%)	Production (kWH)	Consumption (kWh)	Max renewable penetration (%)
ZBF	1,068	50,999	-	14,860	110,815,400	3,704,607	0.1260	81,399,650	68,014,824	4.317
NAS	276	101,339	-	16,767	385,735,700	13,553,190	0.4389	161,749,825	67,984,717	3.057
FB 333	260	116,078	1	16,670	526,551,900	7,759,505	0.5991	185,274,442	67,989,459	2.67
Li-ON	235	163,949	-	16,644	644,806,800	22,816,230	0.7336	261,682,334	67,989,401	1.343

Sensitivity Analysis. In the HOMER software sensitivity analysis, two variables are used for the battery: the lifetime and the minimum state of charge (SOC). The sensitivity analysis results for the SOC variable (with values of 20%, 30%, 40%, and 50%) show that for all battery types, as the SOC percentage increases, so does the cost of energy (COE). Specifically, SOC at 20% (the lowest) results in the lowest COE, while SOC at 50% (the highest) results in the highest COE. This trend is consistent across all battery types. Regarding the battery lifetime variable (with values of 10, 15, 20, and 25 years), the simulation yields two distinct groups. The first group, including NaS and MLI batteries, demonstrates that changes in battery lifetime significantly affect the COE. A longer battery lifetime results in a lower COE, with a 30-year lifetime achieving the lowest COE. In contrast, the second group, which includes ZB and FB 333 batteries shows that changes in the lifetime variable (from 10 to 25 years) do not impact the COE value. This suggests that for ZB and FB 333 batteries, the lifetime does not influence the COE.

3.2 Discussion

Optimizing for Lowest Net Present Cost. The base case architecture of the 100% RE system, which yields the lowest net present cost (NPC) value (the optimization winner), consistently features the SC6U-330P solar PV installation as the dominant component. This indicates that solar radiation has excellent potential in the Nusa Penida area.

Conversely, none of the lowest NPC configurations for the various battery types include the ASW650 wind turbine as part of the renewable energy architecture. This highlights the need for further research into the potential of wind energy as an electricity generation source for Nusa Penida. Additionally, the bio generator only appears once in the base case of the 100% RE architecture when an FB 333-type battery is used. The bio generator emerges as the second preferred renewable energy generator after solar PV.

Sensitivity Analysis. The differences in sensitivity analysis results between the first battery group (NaS and 1 MLI) and the second battery group (ZB and FB 333) are due to variations in their lifetime characteristics. Technically, ZB batteries have a lifespan of up to 30 years, so changes in the variable lifetime from 10 to 25 years do not significantly affect the cost of energy (COE) value. This is in contrast to the NaS and 1 MLI batteries, which have a lifespan of less than 25 years, making their COE more sensitive to changes in lifetime.

4 Conclusion

HOMER software simulation results for optimization of the 100% RE system in Nusa Penida with schematic components consisting of solar PV type SC6U-330P, wind turbine type AWS650, bio generator 500 kW, inverter Sinexcel PWG-100, and four types of batteries ZB, NaS, FB 333 and 1MLI, can be concluded several things as follows:

a. Among the three choices of renewable energy sources, SC6U-330P solar PV, AWS650 wind turbine, and 500 kW bio generator, solar PV is the leading choice as a generation source capable of producing the lowest COE, followed by bio generator and wind turbine.
b. Results of sensitivity analysis for four types of batteries: NaS, 1 MLI, ZB, and FB 333 with variable SOC values (20%, 30%, 40%, and 50%) and lifetime (10, 15, 20, and 25 years) of the battery gives results that the lower the SOC value and the longer the lifetime the battery will provide a lower COE value.
c. Applying a hybrid energy storage system between batteries and other types of storage, such as pump storage, hydrogen, and others, is another alternative storage system that needs to be studied for its optimization value.

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