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RESEARCH ARTICLE

Life Cycle Cost Analysis of PV-Wind-Battery Hybrid Power System at PLN Nusantara Power Brantas Generation Unit Tulungagung

Alfian Budiarmoko *[1] , Heri Suryoatmojo, Feby Agung Pamuji

[1] Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
*Corresponding author (alfian.budiarmoko@plnnusantarapower.co.id).

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Abstract

Indonesia faces significant challenges in meeting electricity demand while reducing environmental impacts from fossil fuel-based generation. Hybrid renewable systems, particularly Photovoltaic–Wind–Battery configurations, offer sustainable alternatives for decentralized applications. This study assesses the technical performance and economic feasibility of an existing hybrid system at PLN Nusantara Power UP Brantas, Tulungagung, based on operational data from 2019 to 2025 and projections over a 20-year lifetime. Emphasis is placed on optimizing load utilization to improve cost efficiency. A comprehensive Life Cycle Cost Analysis (LCCA) and HOMER simulation were conducted to determine the total Life Cycle Cost (LCC) and Levelized Cost of Electricity (LCOE). The calculated LCC was Rp1,611 million, with an LCOE of Rp32,939.33/kWh, while HOMER produced a higher LCOE of Rp39,978.62/kWh. This difference results from the calculation method: HOMER uses a fixed annualized Capital Recovery Factor (CRF), while the LCCA discounts each cost individually using a real discount rate. Sensitivity analysis showed that increasing load utilization by 80% reduced surplus energy from 49% to 8%, lowering the LCOE to Rp18,299.63/kWh. Discount rate variations (3–7%) affected LCOE between Rp36,103.33 Keywords—and Rp30,273.98/kWh. Meanwhile, ±20% changes in O&M costs led to LCOE shifts between Rp31,047.01 and Rp34,831.66/kWh.

Keywords: hybrid, LCCA, LCOE, renewable, sensitivity

I. Introduction

Indonesia faces significant challenges related to rising electricity demand and environmental sustainability due to its continued reliance on fossil fuels, leading to substantial greenhouse gas emissions and jeopardizing national energy security commitments under the Paris Agreement. With the renewable energy share reaching only 13.1% in 2023, considerably below the 2025 target of 23%, accelerating the transition toward renewable energy is essential [1] [2]. This study addresses these challenges by evaluating the technical reliability and economic feasibility of a hybrid renewable energy system consisting of photovoltaic (PV) modules, wind turbines, and battery storage at PT PLN Nusantara Power UP Brantas, Tulungagung (Fig.1). The study emphasizes comprehensive techno-economic analysis and optimization of load utilization to enhance economic viability and environmental benefits [3].

Relevant previous studies offer methodological insights into LCCA, as detailed below. Pantusa et al. [4] conducted an extensive LCC and LCOE analysis for floating offshore renewable energy farms, of costs across definition, design, manufacturing, installation, operation, and dismantling phases. Similarly, Yuan et al. [5] refined LCOE calculation methods by incorporating external cost quantification and detailed internal cost structures, along with critical sensitivity analysis involving capital, raw materials, operation and maintenance, and externalities. Ma et al. [6] presented an advanced lifecycle cost prediction model for wind farms, underscoring the significance of accurate long-term cost estimation for evaluating the economic feasibility of renewable energy projects.

This research contributes to evaluating the economic feasibility of an existing Hybrid PV–Wind–Battery System using operational data from 2019 to 2025, along with projections over its 20-year lifecycle. A detailed LCCA was performed to calculate total project costs and the LCOE. To assess the accuracy and effectiveness of the LCCA method, HOMER software was used as a comparative benchmark [7], employing the same system configuration and input parameters. Sensitivity analyses were also conducted to evaluate the effects of varying load demand, discount rates, and operational costs on overall economic performance. The detailed technical specifications are presented in Table 1, while the design configuration of this research hybrid system is illustrated in Fig. 2.

Fig. 1. Research Location at PT PLN NP UP Brantas – Tulungagung

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TABLE 1. TECHNICAL SPECIFICATIONS OF THE PV–WIND–BATTERY HYBRID SYSTEM COMPONENTS

No.	Equipment	Capacity
1.	Wind Turbine	5 × 500 Wp, HAWT Type
2.	Photovoltaic	8 × 260 Wp, Polycrystalline
3.	Battery Bank	24 units × (2V 1000 Ah)
4.	Wind Turbine Controller	Cut-in Speed: 3 m/s; Stop Charging Safety: 12 m/s Battery Charging: 24 VDC
5	Solar Controller	Rated PV Input Power: 1600 W (24V) 24 V Output
6.	Inverter	Luminous Inverter = 2000 VA EP Solar Inverter = 3000 VA

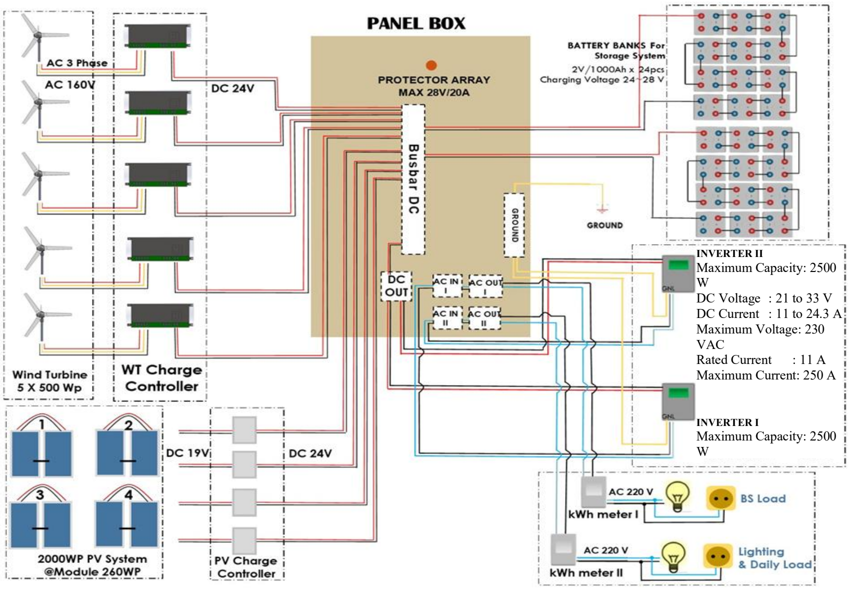

Fig. 2. Hybrid PV-Wind Turbine-Battery Configuration

II. METHODS

A. Life Cycle Cost Analysis

Life cycle cost analysis aims to maximize a product's value throughout its entire lifespan, thus minimizing the customer's overall usage cost. According to the basic guidelines for preparing an LCCA provided by the Department of Education & Early Development, State of Alaska,[8] the LCCA concept for the Hybrid PV-Wind-Battery system in this study is explained in Table 2.

1) Initial Investment Cost

The Initial Investment Cost (IIC) refers to the total initial capital expenditure required to procure and install all components and infrastructure necessary for the operational establishment of the hybrid renewable energy system. A detailed distribution of the IIC components is summarized in the graph shown in Fig.3.

2) Annual Operational Cost

Annual Operational Cost (AOC) refers to the recurring yearly expenses required to maintain the continuous operation and effective management of the hybrid renewable energy system throughout its lifespan [9]. Based on internal salary records, the annual technician cost is determined to be Rp21,662,639.

3) Annual Maintenance Cost

Annual Maintenance Cost (AMC) in LCCA for renewable energy systems is typically determined as a specific percentage of the IIC. In this study, AMC is assumed at 1% of the IIC, aligning with standard industry practices and supported by recent academic literature [10]. AOC and AMC are annual recurring costs. Their Present Value (PV) is calculated using (1):

$$PV_{Annualcost} = A \times [(1 + d)^{t} - 1] / [d\,(1 + d)^{t}] \qquad (1)$$

Where A is the Annual Operational or Maintenance recurring cost, d represent the real discount rate, and t indicates Time (expressed as number of years).

The real discount rate reflects the actual cost of capital, adjusting for inflationary effects, and provides a more accurate measure for economic evaluation over the project's lifetime [11]. Mathematically, the real discount rate is derived using the formula (2):

$$Real\ Discount\ Rate = (Nominal\ Discount\ Rate - Inflation\ Rate) / (1 + Inflation\ Rate) \qquad (2)$$

4) Replacement Cost

Replacement Cost (RC) refers to the expenses associated with replacing essential system components that have shorter operational lifespans compared to the project's total duration, or those affected by unexpected degradation [8]. Present Value of RC is calculated based on planned replacement schedules (3):

$$PV_{RC} = C_{Replacement} / (1+d)^{t} \qquad (3)$$

Where $C_{Replacement}$ represents the RC occurring at year t, d represents the real discount rate, and t indicates the specific year in which the replacement takes place.

TABLE 2. MAIN PHASES OF THE PROCESS FOR THE LIFE-CYCLE COST (LCC) ANALYSIS AND RELATED SUB-COST

Component	Description
Initial Investment Cost	Wind: Turbine, towers, sensors, monitoring devices, rectifier & charge controller, foundation, installation, connection panels. PV: Solar cell module, PV controller, support structure, installation cables, transportation, personnel costs. Battery: Battery station, battery units. Inverter: Luminous/EP Solar inverter. Other: Equipment transportation, personnel costs.
Annual Operational Cost	Labor cost, system monitoring, utility cost, security, miscellaneous costs.
Annual Maintenance Cost	Estimated 1% of Wind, PV, Battery, and Inverter IIC.
Replacement Cost	Unplanned Replacement: Wind turbine blade uprating, MPPT replacement, PLC/data logger addition, voltage/ATS control upgrade. Planned Replacement: Scheduled replacement for Wind, PV, Battery, Inverter components.
End of Life Cost	Estimated 3% of Wind, PV, Battery, and Inverter IIC for decommissioning/disposal at project end.
Residual Value	Estimated 10% of Wind, PV, Battery, and Inverter IIC as salvage value at project end (discounted).

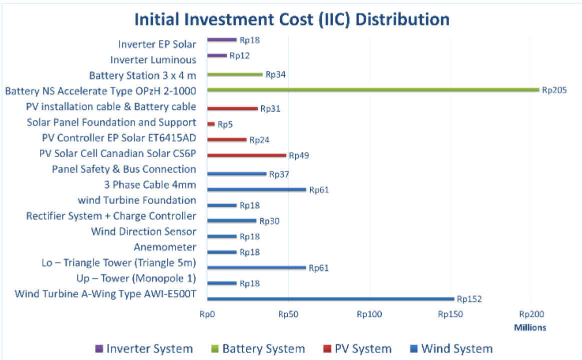

Fig. 3. IIC Distribution for PV-Wind-Battery System

5) *End-of-Life Cost*

End-of-Life Cost (ELC) refers to expenses incurred for dismantling, disposal, or recycling of hybrid renewable energy system components at the end of their operational lifecycle. In this study, the ELC is estimated based on standard practices, calculated as 30% of the IIC [12]. ELC is converted into present value using the real discount rate through the following formula (4):

$$PV_{ELC} = ELC / (1+d)^{t} \qquad (4)$$

Where ELC_{PV} is the present value of the ELC, d represents the real discount rate, and t indicates the project lifetime (20 years). The ELC consistently declines across all components throughout the project's lifetime due to the applied discount rate of 4.89% and inflation rate of 2.8%, reflecting the time value of money, as illustrated in Fig.4.

6) *Residual Value*

Residual Value (RV) represents the estimated economic value remaining in system components after the project's operational lifecycle ends [13]. In this study, the residual value is considered as 10% of the IIC [14].

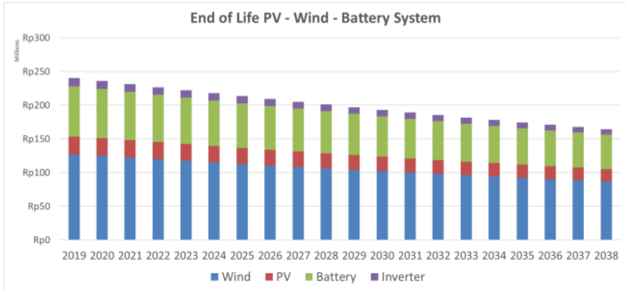

Fig. 4. The End-of-Life Cost Hybrid PV-Wind-Battery System

The present value of RV is calculated as (5):

$$PV_{RV} = RV / (1+d)^{t} \qquad (5)$$

Where RV represents the Residual Value, calculated as 10% of the IIC, d represents the real discount rate, and t denotes the project lifetime, set at 20 years.

7) *Total Life Cycle Cost*

This study utilizes the LCC method to aggregate all associated costs, including the IIC, AOC, AMC, RC, ELC, and RV. The total LCC is expressed by combining all discounted cost components (6):

$$LCC = IIC + PV_{AOC} + PV_{AMC} + PV_{RC} + PV_{ELC} - PV_{RV} \qquad (6)$$

8) *Levelized Cost of Electricity*

Levelized Cost of Electricity (LCOE) represents the average cost per unit of electricity produced (Rp/kWh) throughout the project's lifecycle. It is calculated using the total LCC divided by the total electrical energy production over the 20-year operational lifetime of the hybrid renewable energy system (7):

$$LCOE\ (Rp/kWh) = LCC / Total\ Electricity\ Generated\ (kWh) \qquad (7)$$

The Total Electrical Energy Generated denotes the cumulative electricity produced by the hybrid PV-Wind-Battery system throughout its 20-year operational lifespan, amounting to 48,920 kWh.

B. *HOMER Software Analysis*

Hybrid Optimization Model for Electric Renewables (HOMER) performs three principal functions: simulation, optimization, and sensitivity analysis [7] [15]. The schematic diagram from the HOMER simulation is illustrated in Fig.5.

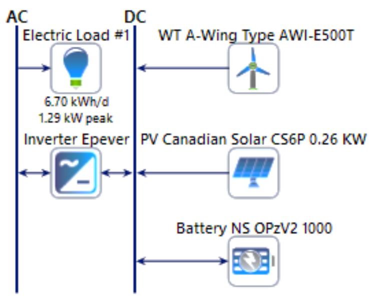

Fig. 5. Schematic Diagram of Hybrid PV-Wind-Battery Power Generation System

1) Energy Resource Analysis

HOMER performs this analysis by incorporating site-specific data to quantify available resources, ensuring precise estimates of renewable energy production.

a) Photovoltaic (PV) Energy Resource Analysis

The PV system uses Canadian Solar 260 CS6P polycrystalline modules, with a rated capacity of 2.08 kW, derating factor of 85%, and conversion efficiency of 13%, as detailed in Table 3. The cost data for all major components are obtained from investment documentation

TABLE 3. PV SYSTEM PARAMETER USED IN HOMER SIMULATION

Parameter	Value/Specification	Units
PV Module Type	Canadian Solar260 CS6P (Polycrystalline)	-
Rated Capacity	2.08	kW
Derating Factor	85	%
Efficiency	13%	%
Temperature Coefficient	-0.424	% / °C
Operating Temperature	43.6	°C
Lifetime	25	years
Capital Cost	129,225,071	Rp
Replacement Cost	24,257,884	Rp
O&M Cost	6,505,674	Rp/year

The mathematical formulation for PV array output [7] in HOMER is defined as (8):

$$P_{PV} = Y_{PV} \,.\, f_{PV} \,.\, (\bar{G}_T / \bar{G}_{T,STC}) \,.\, [1 + \alpha_P (T_C - T_{C,STC})] \quad (8)$$

Where P_{PV} = PV array power output (kW), Y_{PV} = Rated capacity of the PV array at Standard Test Conditions (STC), expressed in kilowatts (kW), f_{PV} = PV derating factor, accounting for losses due to shading, dirt, wiring, and other inefficiencies (fraction, typically between 0.7 to 0.9), $\bar{G}_T$ = Solar radiation incident on the PV array at current time step (kW/m²), $\bar{G}_{T,STC}$ = Incident radiation at Standard Test Conditions (1 kW/m²), α_P= Temperature coefficient of power (%/°C), T_C = PV cell temperature in the current time step (°C), $T_{C,STC}$ = PV cell temperature under standard test conditions (25°C).

b) Wind Energy Resource Analysis

The wind turbine system in this study consists of five units of A-Wing Type AWI-E500T, each with a rated capacity of 0.5 kW, resulting in a total installed capacity of 2.5 kW, as shown in Table 4. The corrected wind turbine power output is calculated using the formula (9):

$$P_{WTG} = (\rho/\rho_0) \,.\, P_{WTG,STP} \quad (9)$$

Where P_{WTG} is the adjusted power output (kW), $P_{WTG,STP}$ denotes the turbine power output under standard temperature and pressure conditions (kW), represents the actual air density at the specific operational location (kg/m³), and ρ_0 is the standard air density, typically taken as 1.225 kg/m³ at sea level.

a) Battery Storage Analysis

The battery storage system is based on NS Accelerate OPzV 2 technology, with specifications summarized in Table 5. HOMER models battery performance using a sophisticated kinetic battery model, which evaluates maximum charging and discharging capabilities of batteries in each simulation time step.

TABLE 4. WIND SYSTEM PARAMETER USED IN HOMER SIMULATION

Parameter	Description / Specification	Units
Wind Turbine Type	Wind Turbine A-Wing Type AWI-E500T	-
Rated Capacity	0.5	kW
Quantity Installed	5	units
Total Capacity	2.5	kW
Lifetime	10	years
Capital Cost	482,775,645	Rp
Replacement Cost	88,433,417	Rp
Annual O&M Cost	9,560,132	Rp/year
Hub Height	10	m

TABLE 5. BATTERY SYSTEM PARAMETER USED IN HOMER SIMULATION

Parameter	Value	Units
Battery Type	NS Accelerate OPzV 2	-
Nominal Voltage	2	V
Nominal Capacity	1.94	kWh
Maximum Capacity	971	Ah
Roundtrip Efficiency	90	%
Maximum Charge Current	146	A
Maximum Discharge Current	979	A
Maximum Charge Rate	1	A/Ah
Lifetime	20	years
Throughput	48	kWh
Capital Cost	285,637,827	Rp
Replacement Cost	0	Rp
Annual O&M Cost	7,805,147	Rp/year

b) Converter Analysis

The converter system, specified as a 5-kW generic inverter-rectifier configuration as shown in Table 6, manages the conversion between direct current (DC) and alternating current (AC). HOMER simulates and evaluates converter performance by analyzing efficiency, sizing, operational lifetime, and associated costs [7]. The inverter converts DC electricity from PV modules or batteries to AC electricity using the efficiency model (10):

$$P_{AC} = P_{DC,in} \,.\, \eta_{inv} \quad (10)$$

Where, P_{AC} = AC output power (kW), $P_{DC,in}$ = DC input power to the inverter (kW), η_{inv} = Inverter efficiency (%).

2) Economic Analysis using HOMER

The two principal economic indicators employed in this analysis are the Net Present Cost (NPC) and the Levelized LCOE).

TABLE 6. CONVERTER SYSTEM PARAMETER USED IN HOMER SIMULATION

Parameter	Specification or Value	Units
Converter Type	Generic Converter (Inverter & Rectifier)	-
Capacity	5	kW
Capital Cost	46,317,803	Rp
Replacement Cost	91,881,247	Rp
Annual O&M Cost	5,720,239	Rp
Inverter Efficiency	95	%
Rectifier Efficiency	9	%
Lifetime	10	years
Relative Capacity	100	%

a) Net Present Cost

NPC represents the aggregated life-cycle cost of the project by annualizing all relevant cash flows (11):

$$NPC = \sum (t = 1 \text{ to } n) \left[C_t / (1+i)^t\right] \quad (11)$$

where C_t is the total cost incurred in year t, i is the annual discount rate, and n is the project lifetime in years.

b) Capital Recovery Factor

HOMER uses Capital Recovery Factor (CRF) to convert the present value of all costs into an equivalent uniform annual cost (12):

$$CRF(i,n) = i.(1+i)^n) / ((1+i)^n\text{-}1) \quad (12)$$

where i is the nominal discount rate, and n is the project lifetime.

c) Annualized Cost

Annualized Cost represents the average annual cost over the project lifetime, calculated by multiplying the NPC by the Capital Recovery Factor (CRF) (13):

$$C_{ann,total} = CRF\ (i,R_{proj}).\ NPC_{total} \quad (13)$$

Where i is the annual real discount rate (%), and R_{proj} is the project lifetime (years), $CRF()$ returns the capital recovery factor.

d) Levelized Cost of Electricity

LCOE quantifies the average cost of energy generation over the system's lifetime (14):

$$LCOE = C_{ann\ total} / E_{served} \quad (14)$$

Where $LCOE$ = Levelized Cost of Electricity (Rp/kWh), $C_{ann\ total}$ = Total annualized cost of the hybrid energy system (Rp/year, E_{served} = Total electrical load served annually (kWh/year).

III. Results and Discussion

A. Economic Feasibility Assessment

1) Life Cycle Cost Analysis Result

This section presents the economic feasibility evaluation of the hybrid PV–Wind–Battery power system using the LCCA approach.

a) Discount Rate and Economic Assumptions

The real discount rate used in this analysis is derived from the average nominal discount rate and national inflation rate in Indonesia between 2019 and 2025. Based on the average BI Rate of 4.89% and an inflation rate of 2.8%, the calculated real discount rate is approximately 2.03%.

b) Life Cycle Cost Components

A visual breakdown of the proportion of each cost component relative to the total LCC is presented in Fig. 6. This pie chart highlights the dominant share of the IIC (48%), followed by AOC (20%), Replacement Cost (12%), and others, illustrating the cost structure of the hybrid system throughout its 20-year lifecycle.

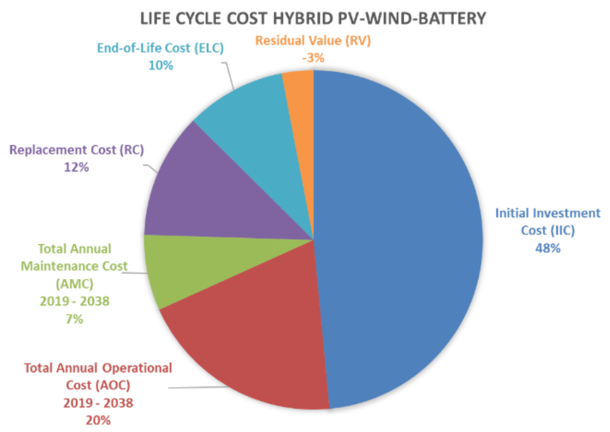

Fig. 6. LCCA Results of PV–Wind–Battery Hybrid Power Plant at Tulungagung

c) LCCA Results Summary

Based on the 20-year project horizon and applying the real discount rate, the total LCC components are summarized at table 7. Consequently, the overall LCC for the Hybrid PV–Wind–Battery System, integrating all discounted financial elements mentioned above, results in a total of Rp1,611,392,227.

Table 7. Life Cycle Cost of Hybrid Power Plant PV-Wind-Battery

LCC Components	Value (Rp)
Initial Investment Cost (IIC)	Rp831,688,361
Total Annual Operational Cost (AOC) 2019 - 2038	Rp338,845,470
Total Annual Maintenance Cost (AMC) 2019 - 2038	Rp124,017,862
Replacement Cost (RC)	Rp204,572,549
End-of-Life Cost (ELC)	Rp164,095,144
Residual Value (RV)	-Rp51,827,159
Total Life Cycle Cost (LCC)	**Rp1,611,392,227**

d) Levelized Cost of Electricity

The LCOE was calculated by utilizing the total LCC described on formula (7). The calculation of LCOE incorporates the total electricity produced by the system throughout its operational period of 20 years, amounting to 48,920 kWh. Applying the above formula and the data provided, the calculated LCOE is Rp32,939.33 per kWh.

2) HOMER Simulation Results

The simulation results generated using HOMER software were employed to evaluate the technical and economic performance of the Hybrid PV–Wind–Battery System implemented at PLN Nusantara Power UP Brantas, Tulungagung. This analysis covers the system's annual energy output, the contribution of each renewable energy source, surplus electricity generation, and key economic indicators such as NPC and (LCOE.

a) Total Renewable Energy Production

According to the simulation, the hybrid system produces a total of 4,785 kWh per year, fully derived from renewable energy sources. The annual electric production breakdown is illustrated in Fig. 7. The energy contributions are distributed as follows:

- Photovoltaic modules (Canadian Solar CS6P) contribute approximately 3,224 kWh/year (67.4%)
- Wind turbines (AWI-E500T) contribute approximately 1,561 kWh/year (32.6%)

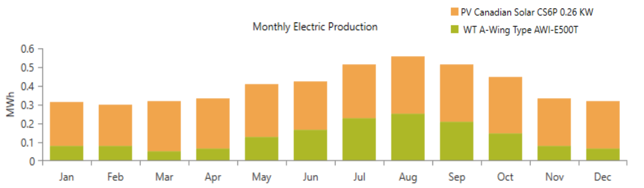

Fig. 7.Electric Production of Hybrid PV-Wind-Battery Power Generation System

b) Load Consumption and Surplus Energy

The system's annual primary AC load consumption is recorded at 2,446 kWh/year, based on actual operational data. Consequently, the system generates a surplus of approximately 2,107 kWh/year, accounting for 44.0% of the total production.

While this indicates a strong production capacity, it also reveals an inefficiency from an economic perspective if the excess energy is not utilized or stored effectively. These figures are summarized in Table 8, which details the contributions of each energy source, annual load demand, and the resulting surplus.

TABLE 8. DETAILED RENEWABLE ENERGY PRODUCTION ANALYSIS

Parameter	Value (kWh/year)	Percentage (%)
PV Module Energy Production	3,224	67.4
Wind Turbine Energy Production	1,561	32.6
Total Renewable Production	4,785	100
Annual Load Consumption	2,446	100
Excess Electricity	2,107	44.0
Renewable Fraction	-	100
Maximum Renewable Penetration	-	3,629

c) Renewable Fraction and Penetration

The simulation indicates a renewable fraction of 100%, meaning that the entire electrical load is served by renewable sources without reliance on fossil fuel-based backup systems. Moreover, the maximum renewable penetration reaches 3,629%, signifying that the system's renewable generation capacity vastly exceeds the actual load, underscoring its technical robustness.

d) Economic Metrics from HOMER Simulation

From an economic standpoint, HOMER simulation estimates the Net Present Cost (NPC) of the system at Rp1,593.6 million and the Levelized Cost of Electricity (LCOE) at Rp39,978.62 per kWh. This LCOE outcome will serve as a benchmark for comparison with the LCCA method, as discussed in the following section.

B. Component Performance Analysis

1) PV Module Performance

The simulation results indicate a robust and stable performance of the PV modules throughout the year. The high-capacity factor of 17.7% demonstrates effective utilization of solar energy resources available in the Tulungagung region. The annual total electricity production from the PV modules reached 3,224 kWh. Detailed PV array performance results are presented in Table 9.

TABLE 9. THE PHOTOVOLTAIC (PV) ARRAY PERFORMANCE RESULTS

Parameter	Value	Units
Total Rated Capacity	2.08	kW
Mean Output	0.368	kW
Daily Mean Output	8.83	kWh/day
Capacity Factor	17.7	%
Total Production per Year	3,224	kWh/year
Maximum Output	1.83	kW
PV Penetration	132	%
Hours of Operation	4,285	hrs/year
Levelized Cost of Production	4,816	Rp/kWh

2) Wind Turbine Performance

Wind turbine power output, consisting of five parallel units (each 500 Wp) of A-Wing Type AWI-E500T, produces a total of 1,561 kWh/year, contributing 32.6% of total renewable energy generated. Detailed performance metrics of the wind turbine system are presented in Table 10.

TABLE 10. WIND TURBINE PERFORMANCE RESULT

Parameter	Value	Units
Total Rated Capacity	2.50	kW
Mean Output	0.178	kW
Capacity Factor	7.13	%
Total Annual Production	1,561	kWh/year
Maximum Output	2.50	kW
Wind Penetration	63.8	%
Hours of Operation	6,978	hrs/year
Levelized Cost of Production	27,860	Rp/kWh

3) Battery Storage Performance

Battery energy storage effectively manages renewable fluctuations, with annual energy input at 1,087 kWh and usable output of approximately 983 kWh, reflecting a storage loss of about 109 kWh per year. The battery autonomy period of 134 hours demonstrates significant reliability and capability to maintain energy supply during intermittent renewable generation conditions. Detailed battery performance metrics, including energy input, output, losses, and autonomy, are presented in Table 11.

4) Converter Performance

The converter operated continuously (8,760 hours/year), successfully supplying the primary AC load throughout the project lifetime. A small annual loss of 129 kWh indicates the high operational efficiency of the inverter at approximately 95%. Detailed converter performance data, including rated capacity, output, capacity factor, and efficiency metrics, are presented in Table 12.

TABLE 11. BATTERY STORAGE PERFORMANCE RESULT

Parameter	Value	Units
Number of Batteries	24	qty.
Nominal Capacity	46.6	kWh
Usable Nominal Capacity	37.3	kWh
Autonomy	134	hours
Lifetime Throughput	1,152	kWh/year
Energy In	1,087	kWh/year
Energy Out	983	kWh/year
Losses	109	kWh/year

TABLE 12. CONVERTER PERFORMANCE RESULT

Parameter	Inverter (kW or kWh/year)
Rated Capacity	5.00 kW
Mean Output	0.279 kW
Minimum Output	0.0127 kW
Maximum Output	1.29 kW
Capacity Factor	5.58%
Hours of Operation	8,760 hrs/year
Energy Output (AC)	2,446 kWh/year
Energy Input (DC)	2,574 kWh/year
Total Losses	129 kWh/year

C. Comparative Analysis

This section compares the economic evaluation outcomes derived from the LCCA and the HOMER simulation, focusing primarily on the resulting LCOE.

1) Overview of LCOE Result

Based on the LCCA calculation, the LCOE of the Hybrid PV–Wind–Battery System over a 20-year project horizon was Rp32,939.33/kWh, derived from a total discounted LCC of Rp1,611,392,227 and an accumulated electricity production of 48,920 kWh. In contrast, the HOMER software simulation, which utilized the same technical configuration and input parameters, yielded a higher LCOE of Rp39,978.62/kWh, despite a slightly lower total NPC of Rp1,593,51,000. These differences are summarized in Table 13.

TABLE 13. COMPARISON OF LCOE RESULTS (LCCA CALCULATION AND HOMER SIMULATION)

Calculation Method	Total LCC / NPC (Rp)	Annual Energy Consumption (kWh/year)	LCOE (Rp/kWh)
LCCA	1,611,392,227	2,446	32,939.33
HOMER Simulation	1,593,51,000	2,446	39,978.62

2) Analysis of Methodological Approach

The key difference between both approaches lies in the capital cost annualization technique. The LCCA method applies present value discounting to each cost component. The present value is calculated over 20 years for the AOC and AMC as shown in equation (1), for RC (3), ELC (4), and RV (5), the present value is determined based on the specific year in which each cost occurs. The total LCC, calculated using these present values in equation (6), is then used to determine the LCOE as shown in equation (7).

In contrast, HOMER calculates the LCOE (14) by first determining the annualized cost (13), which is obtained by applying the CRF (12) to convert upfront capital costs into a uniform annual cost over the project duration. This standardization using CRF allows for direct comparison across different system configurations.

This methodological difference significantly impacts the resulting LCOE, with the LCCA method yielding a 21.4% lower LCOE than HOMER. The LCCA approach more accurately reflects actual financial flows, making it a more precise tool for post-implementation analysis.

D. Environmental Impact Assessment

Environmental impact assessment plays a pivotal role in evaluating the broader implications of renewable energy system deployment beyond mere financial and technical viability. This section analyzes the emission reduction achieved by the hybrid PV–Wind–Battery system.

1) Emission Analysis

Using HOMER simulation, the total annual renewable energy generation of the hybrid system is 4,785 kWh/year, comprising 67.4% from the photovoltaic system (3,224 kWh/year) and 32.6% from the wind turbines (1,561 kWh/year). Considering the Indonesian national emission factor for conventional power plants is approximately 0.87 kg CO_2 per kWh (National Energy Council, 2020), the annual avoided emissions can be calculated as follows (15):

$$\text{Avoided } CO_2\ (kg/year) = \text{Total Renewable Production } (kWh/year) \times \text{Emission Factor } (kg\ CO_2 / kWh) \quad (15)$$

Thus, the total emissions avoided by the system are:

$$4{,}785 \text{ kWh/year} \times 0.87 \text{ kg } CO_2 / \text{kWh} = 4{,}163 \text{ kg } CO_2 / \text{year} \approx 4.16 \text{ ton } CO_2 / \text{year}$$

E. Economic Sustainability Evaluation

According to LCCA calculations, the hybrid system's LCOE is Rp32,939.33 per kWh, which notably exceeds the electricity tariffs set by PLN as of March 2025[18], ranging from Rp1,352 to Rp1,699.53 per kWh across customer categories. This indicates that, from an economic standpoint, the system remains less competitive compared to conventional grid electricity under current pricing conditions.

F. Sensitivity Analysis

Sensitivity analysis was conducted to assess the robustness of economic feasibility under varying discount rates, operational costs, and load demand, while also identifying key risk factors [19].

1) Discount Rate Variation

The discount rate significantly affects the LCCA, particularly influencing the NPC and the LCOE. The baseline discount rate applied in this study was 4.89%. The sensitivity analysis varied the discount rate within a reasonable range, from 3% to 7%, as presented on Table 14.

2) Operational and Maintenance Cost Variation

The baseline annual O&M cost in this study comprises Rp21.7 million for operational expenses and Rp7.9 million for maintenance. A sensitivity analysis was conducted by examining the impact of a ±20% variation in these costs to evaluate their influence on financial performance, as presented in Table 15.

TABLE 14. SENSITIVITY ANALYSIS OF DISCOUNT RATE VARIATION

Discount Rate (%)	NPC (Rp million)	LCOE (Rp/kWh)	Impact Analysis
3	1,766.2	36,103.33	Higher cost due to lower discounting of future expenditures
4.89 (Baseline)	1,611.1	32,932.65	Baseline condition (actual scenario)
7	1,481.0	30,273.98	Lower cost due to greater discounting of future expenditures

TABLE 15. SENSITIVITY ANALYSIS OF OPERATIONAL AND MAINTENANCE COSTS

O&M Costs Scenario	AOC (Rp million / year)	NPC (Rp million)	LCOE (Rp / kWh)	Impact Analysis
-20% (Reduced)	23.7	1,518.8	31,047.01	Reduced costs significantly enhance financial feasibility
Baseline (0%)	29.6	1,611.4	32,939.33	Baseline scenario (actual condition)
+20% (Increased)	35.5	1,704.0	34,831.66	Increased costs substantially reduce financial attractiveness

3) Load Utilization Scenarios

A sensitivity analysis was conducted to assess how increasing annual load affects the LCOE. As shown in Table 16, higher load utilization reduces excess energy and significantly lowers the LCOE. At full load absorption (100% utilization), the system achieves optimal efficiency with zero surplus energy and the lowest LCOE value of Rp16,837.96/kWh. This finding underscores the importance of aligning energy production with actual load demand to enhance cost-effectiveness.

TABLE 16. LOAD VARIATION IMPACT ON LCOE

Scenario	Annual Load (kWh/year)	Total Production (kWh/year)	Excess Energy (kWh/year)	LCOE (Rp/kWh)
Base Case	2,446	4,785	2,339 (48.9%)	32,939.33
+20% Load	2,935	4,785	1,849.8 (38.7%)	27,449.45
+40% Load	3,424	4,785	1,360.6 (28.4%)	23,528.10
+60% Load	3,914	4,785	871.4 (18.2%)	20,587.08
+80% Load	4,403	4,785	382.2 (7.99%)	18,299.63
100% Utilization)	4,785	4,785	0 (0%)	16,837.96

IV. CONCLUSION

This research assessed the economic performance of a hybrid PV–Wind–Battery energy system at PLN Nusantara Power UP Brantas, Tulungagung, through a detailed LCCA. The analysis indicated a total investment of approximately Rp1,611 million over a 20-year period, resulting in an LCOE of Rp32,939.33/kWh. In comparison, the HOMER simulation produced a higher LCOE of Rp39,978/kWh, primarily due to differences in capital cost annualization methods. HOMER applies a uniform CRF, while LCCA uses present value discounting based on real cash flows.

Furthermore, sensitivity analyses revealed that optimizing electricity load demand significantly improves the system's economic attractiveness. Specifically, increasing load utilization by 80% reduced energy surplus from 49% to approximately 8%, thereby lowering the LCOE to Rp18,299.63/kWh. Although the initial LCOE exceeded PLN's 2025 electricity tariff of Rp1,352/kWh, strategic load management and accurate system sizing markedly enhance economic viability. Additionally, the environmental assessment underscores notable sustainability benefits, with an estimated annual reduction of 4.16 tons of CO_2 emissions achieved through a 100% renewable energy fraction.

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