Original scientific paper

Techno-Economic Analysis of Photovoltaic Systems to Realize Sustainable Development Goals (SDGs)

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Abstract: Dependence on fossil fuels and environmental impacts such as carbon emissions and global warming are major challenges in energy sustainability. This study aims to conduct a techno-economic analysis of a hybrid solar power plant (PVP) system with a capacity of 46 kWp in Beloh Hamlet, Mojokerto Regency. Performance evaluation was conducted using PVsyst software to assess the energy efficiency and economic viability of the system. The simulation results show that the system produces an output power of 189.25 kWh per day or 69,077 kWh per year, with a Performance Ratio (PR) reaching 75.7%. From an economic perspective, the analysis shows a Net Present Value (NPV) value of IDR 404,631,838, with a Payback Period (PP) in year 9 and a Break-Even Point (BEP) in year 8. The system also has a Return on Investment (ROI) of 215% in 25 years. In addition, the implementation of this system contributes to the achievement of the Sustainable Development Goals (SDGs), especially SDG 7 (Clean and Affordable Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Settlements). With an estimated carbon emission reduction of 1,118 tons in 25 years, this study confirms the potential of solar PV as a sustainable solution to support energy transition in rural Indonesia.

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1   Introduction

The global imperative to transition from fossil fuels to renewable energy has intensified in recent decades, driven by growing environmental concerns, energy security considerations, and international sustainability commitments, particularly for achieving Sustainable Development Goals (SDGs) through energy independence and self-sufficiency in residential and community settings [1]. Energy challenges related to global warming, environmental degradation, and supply security increasingly demand coordinated and multifaceted solutions across technological, economic, and policy dimensions, with SDG 7 (affordable and clean energy) serving as a fundamental framework driving solar power adoption and implementation for meeting electrical needs in both developed and developing regions worldwide [2 – 6].

Indonesia's electrical consumption demonstrates a significant upward trajectory, with projections indicating increases of 11–12% by 2025 and 6–7% by 2050, ultimately reaching substantial demands of 576.2 TWh and 2,214 TWh respectively, which highlights the urgent need for expanded and diversified energy generation capacity [7]. Within this national context, Mojokerto Regency represents a microcosm of these trends, having reported a notable 9.18% consumption increase in 2022, with electricity primarily supplied by the State Electricity Company (PT. PLN) through fossil-based sources comprising 37.62% coal and 33.40% petroleum, which together constitute the dominant energy generation methods [8]. These conventional fossil sources not only face long-term supply constraints but also contribute significantly to carbon emissions and environmental degradation, thereby necessitating the development and implementation of renewable alternatives to meet both growing energy demands and SDG targets for sustainable development and climate action.

Indonesia's advantageous geographical position near the equator provides substantial solar energy potential across its archipelagic territory, with average solar radiation levels consistently measuring 4.8 kWh/m²/day (equivalent to an impressive 112,000 GWp of potential capacity), making solar power generation increasingly viable and attractive for residential and community electricity supply while simultaneously advancing the national agenda for renewable energy utilization and technology adoption [9]. Within this broader geographical context, Beloh Hamlet, situated in western Mojokerto Regency, offers particularly favorable conditions for solar energy harvesting and conversion, with measured radiation levels of 5.35 kW/m²/day (exceeding the national average) and consistent average temperatures of 28.1°C throughout the year, collectively

presenting an optimal location for solar power implementation and system performance evaluation in real-world conditions.

This study conducts a comprehensive techno-economic analysis of a 46 kWp hybrid solar power system for Beloh Hamlet, employing cash flow ratio analysis and break-even determination methods. The research addresses critical literature gaps in the Indonesian context by: (1) integrating comprehensive technical and economic parameters; (2) analyzing a medium-capacity hybrid system for community electrification; (3) assessing East Java's tropical climate implications; (4) correlating outcomes with SDGs 7, 9, and 11; and (5) implementing a holistic methodology combining PVsyst simulation, environmental impact quantify-cation, and 25-year economic projections that transcends conventional single-dimensional approaches in current research.

2   Related Research

The analysis of solar power generation systems has been the focus of numerous studies with diverse methodological approaches and economic evaluation frameworks. **Table 1** presents a comparative overview of recent influential studies, highlighting methodological choices and economic evaluation parameters. These studies show substantial contributions to the technical and economic aspects of solar power systems, but few integrate economic parameters with technical performance in the Indonesian tropical context, and the explicit link between solar power systems and the SDGs framework remains largely unexplored.

Table 1
Relevant Research.

Ref.	Method			Economic Variables					Economic Parameters										
	Design RETscreen	Design Homer	Design PVsyst	Investment costs	O&M costs	interest rate	Cost of Energy	Taxes	IRR	ROI	NPV	NPC	BCR	Payback Period	Simple Payback	LCOE	NPW	PI	DPB
[9]	✓			✓	✓	✓	✓		✓		✓	✓	✓	✓					
[10]	✓		✓	✓	✓	✓	✓	✓		✓	✓			✓		✓			
[11]	✓			✓	✓	✓	✓		✓		✓						✓		
[12]		✓		✓	✓	✓			✓	✓		✓			✓				
[13]	✓			✓	✓	✓			✓		✓							✓	✓

Rehman's feasibility analysis in Saudi Arabia resulted in a 10 MW grid-connected solar power plant designed for the Bisha area, selected for its superior

solar radiation intensity and extended irradiation duration [9]. Obeng et al. demonstrated that solar installations utilizing three distinct PV models generated annual electrical energy exports of 67,315 MWh, 67,506 MWh and 68,991 MWh respectively, with positive NPV values, cost ratios exceeding 1.0, and payback periods of 7.2 years for silicon crystal systems and 6.4 years for thin film systems [10]. Ray et al. examined the economic viability of an 80 kWp capacity solar system that produced 89.83 MWh annually, yielding an NPV of IDR 81,346,406 and an IRR of 0.54% [11]. Dekkiche et al. determined that optimally designed grid-connected hybrid PV/RF systems delivered superior economic performance with low NPC and COE values, positive ROI, and a minimum simple payback period of 7.79 years [12]. Peprah et al. implemented ET screen design methodologies for solar installations, concluding that grid integration without storage represented the optimal investment configuration [13].

Building upon these studies, this research conducts a comprehensive analysis of both technical and economic feasibility dimensions for a 46 kWp hybrid solar power plant in Beloh Hamlet, Mojokerto Regency. The present study extends beyond previous research by employing global benchmarking standards to facilitate comparative assessment of performance ratios and implementing thorough cost-benefit analyses across multiple economic parameters. This approach addresses methodological limitations in existing literature while providing context-specific insights for tropical regions with similar geographical characteristics.

3   Research Methods

The solar power plant system analyzed in this research is a centralized hybrid solar power plant with a total installed capacity of 46 kWp. The system is designed to integrate solar panels, inverters, and battery storage to enhance energy reliability and efficiency, ensuring optimal performance for rural electrification. This system consists of solar panels, batteries, and inverters, which are configured to ensure reliable energy generation and distribution. Fig. 1 illustrates the hybrid system used in this study.

Solar panels convert solar radiation into electrical energy, which is regulated by a DC-DC converter to charge the battery. The stored energy flows to the inverter, converting DC to AC, and is then distributed through the Main Distribution Panel (MDP) and electric pole cables to each house. If solar and battery power are insufficient, the system manually switches to the electricity grid.

Data processing in this study uses data visualization techniques, with PVsyst for primary visualization and MATLAB for reprocessing data not displayed in PVsyst. The research follows two scenarios: direct technical calculations using mathematical equations and simulations in PVsyst combined with economic

calculations. Data not covered by PVsyst is processed in MATLAB for further technical and economic analysis.
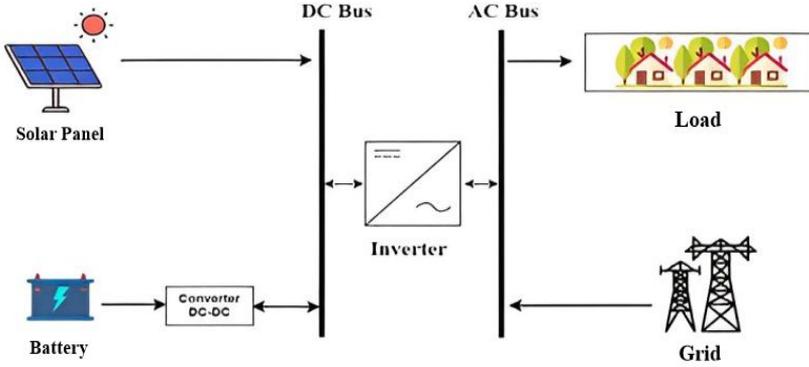

Fig. 1 – *Solar power plant system schematic.*

3.1 Technical analysis

Solar radiation intensity is the amount of energy received by a surface per unit of time. The intensity of solar radiation at the research location was obtained through the Meteonorm database. Solar radiation data is used to evaluate the solar energy potential at the research location. In estimating the capacity of the solar power plant to be built, electricity load data at the research location is required, with daily energy calculations obtained using (1) [14].

$$W_{Supply} = (SF \times W_{demand}) + W_{demand}. \tag{1}$$

After estimating the daily energy at the research location, the next step in designing a solar power plant is to calculate the peak power and energy generation by taking into account the power losses in the PV module, where the power and energy generated can be calculated using (2) as follows [15].

$$P_{solar\ power} = \frac{W_{Supply}}{PSH} + \left(15\% \times \frac{W_{Supply}}{PSH} \right) \tag{2}$$

After estimating the load requirements used, the next step in planning the design of a solar power plant is to calculate the components to be used, which consist of PV modules, batteries, and inverters [16, 17].

Calculation of PV amount:

$$N_{PV} = P_{solar\ power} / P_{PV}. \tag{3}$$

Inverter calculation:

$$P_{INV} = P_{Demand} + (SF \times P_{Demand}), \tag{4}$$

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$$N_{INV} = \frac{P_{INV}}{P_{single\ INV}} \tag{5}$$

Analysis of the potential results of solar energy received by the panel is obtained through graphs from PVsyst software simulations, where the amount of electrical energy produced by the PV system is also needed to determine the energy production of the system built, so the next step in analyzing solar power generation systems technically is to review the results of the system's daily energy output through graphs of PVsyst simulation results. In designing a solar power plant, it is necessary to know the output power of the generating system to determine how much energy can be generated and distributed to the load at the research site, so the next step is to analyst the system output results obtained through graphs from PVsyst software simulations.

The efficiency of the solar PV system refers to the extent to which the system can convert solar energy into electrical energy, so the next step is to evaluate the PVsyst simulation results related to the efficiency of the solar power generation system. The sustainability of the solar power generation system can be seen from the resulting performance ratio with an ideal range of 70% - 90% [18], where after knowing the sustainability of the system, an analysis is carried out regarding other SDG targets generated to realize the SDGs.

To calculate the CO2 gas emissions (e_{CO2}) that can be reduced by using solar power plants for 25 years, the project life can be determined and adjusted to the longest component life [19], where the calculation of CO2 gas production can use (8):

$$e_{CO_2} = E_{daily} \cdot \text{EF} . \tag{8}$$

3.2 Economic analysis

Service costs in this research are calculated 12 times a year where the cost reference refers to the UMR at the research location. In carrying out an economic analysis, the next step is to calculate operational costs, which in the research are calculated at 1% of the initial investment costs through (9) [20 – 23]:

$$CO = 1\% \times \text{ Initial investment costs} . \tag{9}$$

Furthermore, additional costs allocated for maintenance can be calculated using the following (10):

$$C_O M = \text{Initial investment costs} / 25 \text{ years} . \tag{10}$$

To find out the COE of a microgrid system, the following equations can be used:

$$CRF(\%) = \frac{i(1+i)^n}{(1+i)^n - 1} , \tag{11}$$

$$COE = \frac{C \times CRF}{\sum_{d=1}^{365} W_{annual}}. \tag{12}$$

In analyzing a project economically, it is necessary to know the cash flow of a project to be built. The annual income is obtained through (13):

$$I = W_{Annual} \times TL. \tag{13}$$

Net Present Value (NPV) is an economic parameter taken into account in this study, where to find out the NPV value can be calculated using (14) [24 – 27]:

$$NPV = -Co + \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_t}{(1+r)^t} \tag{14}$$

In the economic analysis of a project, it is necessary to calculate the payback period of the investment that has been made [28], where to calculate PP, (15) can be used:

$$PP = \frac{n + (a - b)}{(c - b)} \times 1 \text{ year}. \tag{15}$$

The break-even point (BEP) in economic analysis is used to determine the point where the investment that has been made reaches a break-even position, with the calculation of BEP using (16) [29, 30]:

$$BEP = \left(\frac{FC}{COE - VC} \right). \tag{16}$$

Return on Investment (ROI) in economic analysis is used to measure the effectiveness and profitability of an investment, with ROI calculation using (17) [31 – 34]:

$$ROI = \frac{NP}{C} \times 100\%. \tag{17}$$

3.3 Basic parameters

The techno-economic analysis of the solar PV system relies on key parameters to ensure feasibility and reliability. Meteorological data from Meteonorm 7.3 (1991–2010 for irradiation, 2000–2009 for temperature) includes a GHI of 5.35 kWh/m²/day, ambient temperature of 28.1°C, relative humidity of 78%, and wind speed of 2.3 m/s. Seasonal irradiation drops by 8% during the rainy season (Nov-Mar). Economic factors include a 3.5% annual inflation rate (based on Indonesia's 5-year trend) and a 2% yearly electricity price increase per PT PLN policy. Component lifespans are 25 years (solar panels), 10 years (inverters), and 7 years (batteries), with replacements as scheduled. The interest rate is 8% (BRI bank). Technical factors include 0.5% annual panel degradation, 19.8% PV efficiency, 15% system losses, and safety factors of 25% (load reserve)

and 20% (inverter). Additional losses include soiling (2%), mismatch (2%), DC cables (1.5%), AC cables (1%), and high temperature (4.5%). **Table 2** summarizes the parameters.

Table 2

Basic parameters used in the study.

Category	Parameters	Value
Meteorology	Global Horizontal Irradiation (GHI)	5.35 kWh/m²/day
	Average Ambient Temperature	28.1°C
	Average Relative Humidity	78%
	Average Wind Speed	2.3 m/s
	Seasonal Variation (Rainy Season)	Irradiation decrease up to 8%
Economic	Inflation Rate	3.5% per year
	Electricity Price Increase	2% per year
	Solar Panel Lifetime	25 years
	Inverter Lifetime	10 years
	Battery Lifetime	7 years
	Interest Rate	8%
Technical	Solar Panel Degradation	0.5% per year
	PV Module Conversion Efficiency	19.8%
	Power Losses	15%
	Load Safety Factor	25%
	Inverter Safety Factor	20%
	Soiling Losses	2%
	Mismatch Losses	2%
	DC Cable Losses	1.5%
	AC Cable Losses	1%
	Temperature Losses	4.5%

3.4 PVsyst simulation and validation process

This research utilizes PVsyst software version 7.2 for simulating and analyzing solar PV system performance. Developed by the University of Geneva, PVsyst is widely used for comprehensive photovoltaic system planning, simulation, and data analysis. It was chosen for its detailed simulations, extensive component database, and consideration of technical and meteorological parameters. Key input parameters include meteorological data from Meteonorm for Beloh Hamlet, a 46 kWp system with 8 parallel strings (23 modules per string), 250 Wp monocrystalline solar modules, a 20 kW inverter, a 100 Ah

battery, daily load profiles from a survey of 40 houses, system loss parameters (temperature, soiling, mismatch, cable resistance), and a 15° north-facing panel orientation. Since the system is still in the planning stage, the PVsyst simulation results were not validated with field measurements. However, reliability is ensured through calibrated Meteonorm data, Performance Ratio (PR) comparisons with global benchmarks, sensitivity analysis of key parameters, and expert review. Limitations include uncertainties in long-term meteorological projections, simplifications in shading models, estimated component degradation, and challenges in modeling battery-hybrid system interactions. To mitigate these, safety margins were applied, and sensitivity analyses were conducted to assess parameter variations.

4   Results and Discussion

Beloh Hamlet is located in Mojokerto Regency. Based on data from the Global Solar Atlas, this area has a latitude of 7.5578°LS and a longitude of 112.4°BT. Based on electricity load data in Beloh Hamlet with a total of 40 households, there are 40 houses with a daily energy of 166,820 Wh or 166.82 kWh. In this area, PT PLN still supplies the overall daily electricity demand for 24 hours.

4.2 Technical analysis

This can be obtained through the Meteonorm database contained in the PVsyst software to determine the intensity of solar radiation in the research area. Fig. 2 explains the solar radiation intensity data in Dusun Beloh.
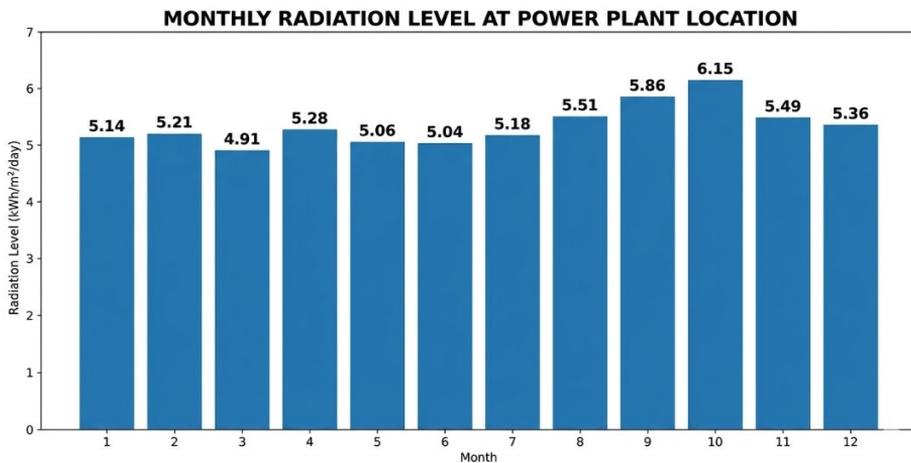

Fig. 2 – *Solar Irradiation Intensity.*

Based on Fig. 2, the maximum radiation intensity occurred in October at 6.15 kWh/m^2 /day and the minimum occurred in March with an intensity of 4.91 kWh/m^2 /day. The average solar radiation at the study site from January to December was 5.35 kWh/m^2 /day.
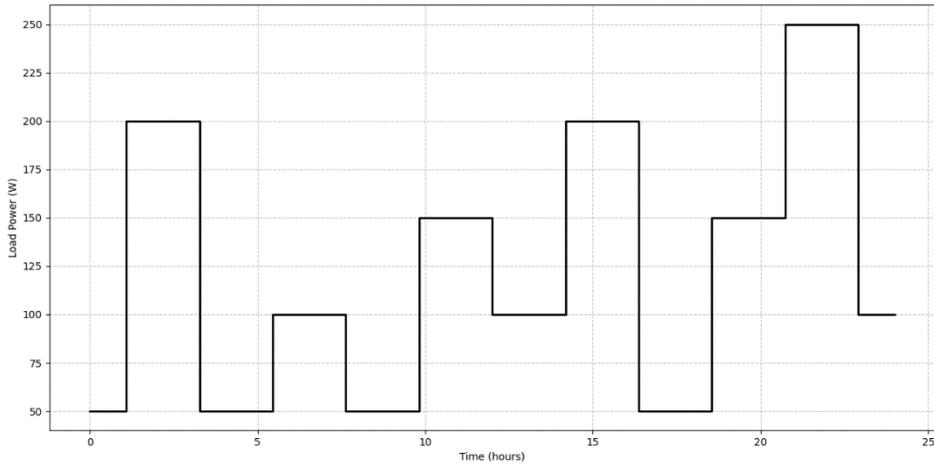

Fig. 3 – *Beloh Hamlet's Daily Load.*

Daily Load is Based on Fig. 3, the peak power at the research location occurs between 19:00 and 21:00, reaching 12,000 W, while the minimum load power of 3,860 W is recorded at 08:00–09:00 and 15:00.

Table 3
Load Data.

Load	Amount	Power [W]	Time [Hour]	Daily energy [Wh]	*Pdemand* [W]
Lamp (LED/ Fluo)	208	10	10	20800	2080
TV/PC/Mobile	36	75	4	10800	2700
Home Appliances	25	250	2	12500	6250
Refrigerator	32	115	24	88320	3680
Washing machine	10	320	2	6400	3200
Fan	35	100	8	28000	3500
Total	346	870	50	166820	21410

Table 3 Based on the load data above with the addition of a safety factor of 25% as a backup in case of additional load [35], then through (1), the daily energy requirement (Wsupply) is 208525 Wh. Based on (2) with an average irradiation

(PSH) of 5.35 kWh/m²/day, and power losses (Plosses) assumed to be 15% because all components used are new components, the peak power of the solar power plant is 46 kWp.

The main components of a solar power plant consist of solar modules, inverters, and batteries. Based on (3), the number of solar modules required for a 46 kWp solar power plant is 184 units connected in series and parallel, there are 8 strings of solar panels connected in parallel and each string of solar panels consists of 23 units of solar panels. The type of PV used is 250 Wp monocrystalline. The reason for choosing this type of monocrystalline module is because it can work in cloudy weather and has a high electron absorption capacity. Furthermore, using (4) and (5), assuming a safety factor of 20% [36], the 46 kWp PV plant requires a 2-unit 20 kW inverter. Furthermore, to calculate the battery requirement for a 46 kWp solar power plant, using (6) and (7), the total battery requirement is 224 units. The 100 Ah battery from the CS Power brand was chosen because it has a fairly high efficiency of 97%.

Based on Fig. 4, the average solar energy received by the panels is 5,433 kWh/m²/day. The maximum solar energy received by the panel is 6.02 kWh/m²/day, namely in October and the minimum solar energy received by the panel is 4.81 kWh/m²/day in January.
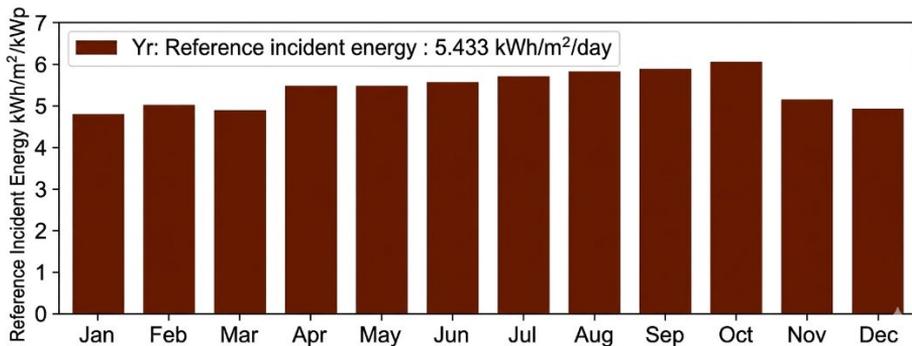

Fig. 4 – *Reference Incident in Collector Plane.*

Fig. 5 displays a graph between the global incident col. plane and the solar energy available for conversion to electrical energy, the output of the graph should be a straight line that slightly saturates for large values of irradiance. In the graph you can see a slight curve showing the effect of temperature.

In Fig. 6 below, it is shown that the minimum temperature was 21.4°C with a total energy of 10.1 W/m² and the highest temperature reached 76°C with a total energy of 1,101 W/m² with the average amount of energy generated in a year being 458.9 W/m².

In Fig. 7 it can be seen that the output of the PV system reaches a maximum value of 1100 W with a minimum value of 200 W with an average output of 5,600 W. However, the distributed power also shows that most of the system operating time is at an energy output of 400 – 800 W. This can be noted as leakage from the PV system.
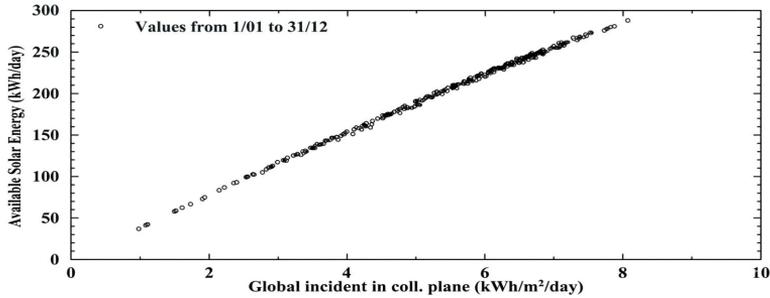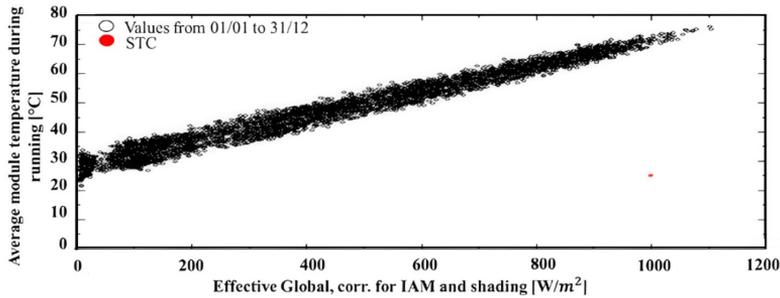

Fig. 5 – *Daily Input/Output Diagram.*
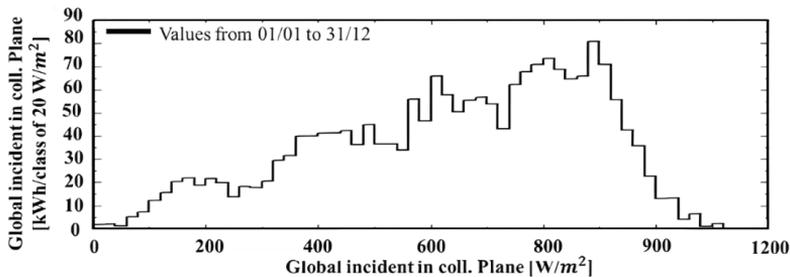

Fig. 6 – *Array Temperature vs. Effective Irradiance.*

Fig. 7 – *Incident Irradiation Distribution.*

Based on the simulation results in Fig. 8, the output power of the hybrid PLTS system with a capacity of 46 kWp after power losses is 189.25 kWh per day or equivalent to 69077 kWh/year which is able to supply the load in Beloh Hamlet, Mojokerto Regency of 166.82 kWh/day. By using the average electricity usage of a 1-storey AC house in Indonesia of 1.1 kW, the output power of the

PLTS system of 189.25 kWh is equivalent to the electrical power of about 7 1-storey AC houses. The simulation results also show that the energy supplied to the load (Y_f) averages 4.4 kWh/kWp/day with different power production each month. This difference is also caused by the calculation of the global average radiation level in each month which is different. Power losses on PV (L_c) averaged 0.94 kWh/kWp/day, and system losses (L_s) averaged 0.09 kWh/kWp/day.
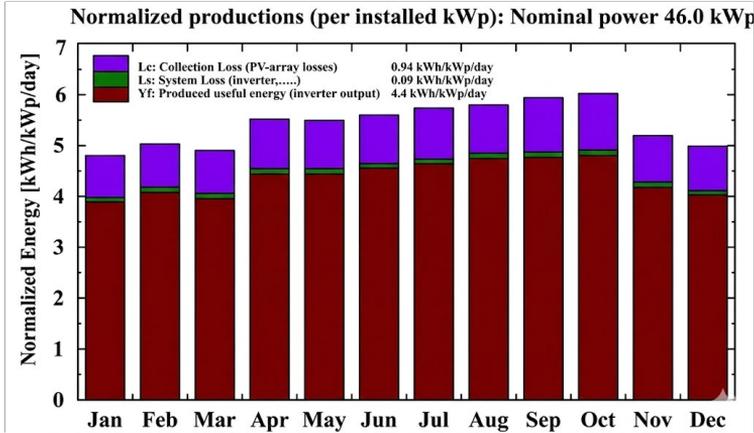

Fig. 8 – *Normalized Productions.*

4.3 System efficiency

In Fig. 9 performance ratio [34, 37]. The system efficiency based on PVsyst simulation results reached 75.7%, higher than some previous studies which ranged from 70 – 73%. This difference is due to the use of a more optimised panel configuration and a more efficient energy storage system, higher than some previous studies which ranged from 70 – 73%.
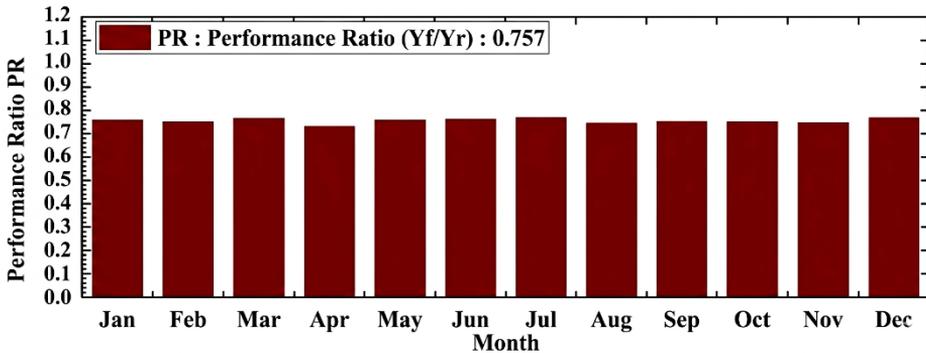

Fig. 9 – *Performance ratio.*

The solar power generation system with a Performance Ratio (PR) of 75.7% in this study is considered sustainable, fulfilling the ideal PR criteria between 70%-90% [38]. This success supports the achievement of SDG 7 on clean and affordable energy. In addition, this system supports SDG 9 by being an innovation in the renewable energy sector and becoming an example for adoption by the community. The implementation of solar power generation also supports SDG 11 for sustainable cities and neighbourhoods, providing environmentally friendly energy.

The daily energy demand at the study site is 166.82 kWh, with a CO_2 emission factor of 0.743 CO2/kWh. If using fossil energy generation, daily CO_2 emissions are 124.33 kg. In a month it reaches 3729.92 kg, and in a year it reaches 44759.14 kg. With solar power generation, clean electrical energy is generated without CO_2 emissions for 25 years, reducing emissions by 1,118 tonnes/25 years. Thus, the solar power generation system is considered sustainable and supports the reduction of CO_2 emissions [39]. A graph of the growth of CO_2 gas emissions when using fossil energy is presented in Fig. 10.
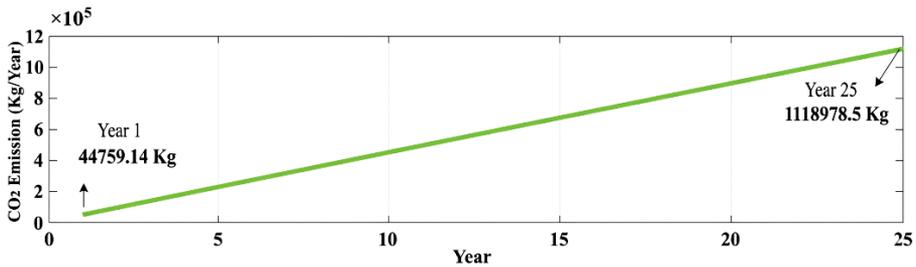

Fig. 10 – *CO2 Gas Emissions.*

4.4 Economic analysis

The servicing cost for the hybrid solar power plant in Beloh Hamlet is calculated at IDR 3,603,829. This cost refers to the minimum wage of Mojokerto Regency with a work period of 12 times a year. Taking into account the tax on the purchase of each component, the initial investment cost calculation is obtained according to **Table 4** as follows:

Table 4
Initial Investment Costs.

No	Component	Amount	Unit price	Unit price [+20% taxes]	Total
1	PV 250 Wp	184	IDR 1.900.000	IDR 2.280.000	IDR 419.520.000
2	Inverter 20 kW	2	IDR 30.000.000	IDR 36.000.000	IDR 72.000.000
3	Battery 100 Ah	224	IDR 1.200.000	IDR 1.440.000	IDR 322.560.000
Total					**IDR 814.080.000**

In this study, the Operation and Maintenance (O&M) cost is calculated at 1% of the total initial investment, resulting in IDR 8,140,800 based on (9). Meanwhile, the additional cost for maintenance is calculated by (10), resulting in IDR 32,563,200. With a CRF value of 0.0936% (equation (11)) and a cost of operation (COE) result of IDR 1,001/kWh for 25 years (equation (12)), the PLTS tariff is slightly lower than the PT PLN tariff, which is currently at IDR 1,500/kWh.

Fig. 11 shows that in the first year, the cash flow is still negative until the 7th year the cash flow is still negative, namely –IDR 97,120,344. Revenue each year is constant at IDR 114,167,437 so that in year 7 the incoming revenue still cannot cover the capital that has been invested. This is due to O&M costs of Rp 8,140,800 and service costs of IDR 3,603,829 each year. Furthermore, in year 8, the cash flow began to look positive, namely IDR 5,302,460 positive cash flow until year 25 with a nominal value of net cash flow of IDR 1,746,490,200.
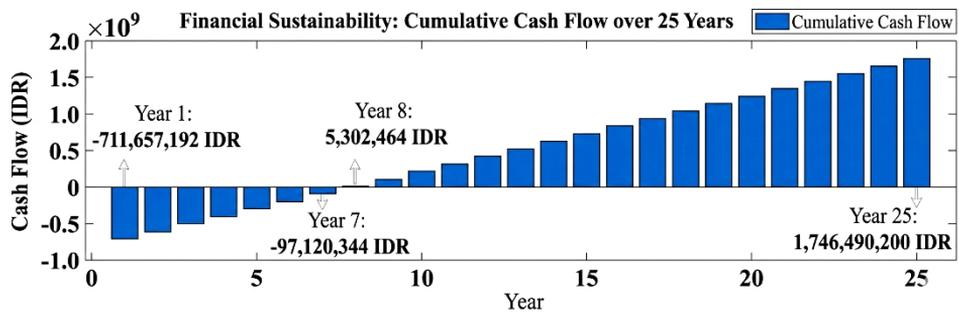

Fig. 11 – *Cash flow.*

4.4.1 Net Present Value (NPV)

Based on Fig. 12, it can be seen that in year 1, the NPV value is negative, namely –IDR 708,369,410. But in year 2, the NPV value is positive, namely IDR 97,880,176. The NPV value is positive from year 2 to year 25, where the NPV value is IDR 16,670,490. The 8% interest rate used refers to the BRI bank interest rate. Then, using the calculation equation (14), the total NPV is positive, which is IDR 404,631,838. This means that the project is feasible to run because the NPV value > 0 or positive. The NPV calculation using the second experiment was carried out using an interest rate from another bank of 14%, resulting in a negative total NPV of IDR 27,415,487, so it can be seen that the appropriate interest rate applied in this study is 8%.
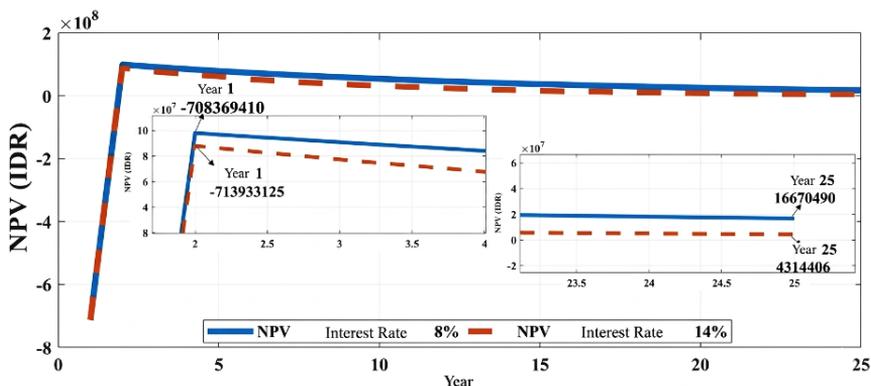
Fig. 12 – *Net Present Value.*

4.4.2 Payback Period (PP) and Break Event Point (BEP)

In Fig. 13, it can be seen that the payback period for a 46 kWp solar power plant project with an initial investment cost of IDR 814,080,000 is in year 9 with a cumulative cash value of IDR 107,725,272.
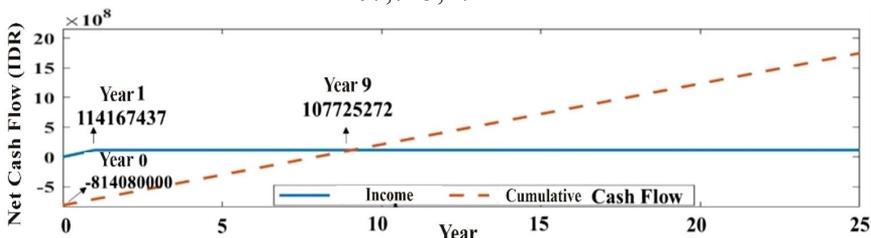

Fig. 13 – *Payback period.*

Based on calculations using (16), the results obtained are represented in graphic Fig. 14, where it can be seen in the graph that the break-even point value for the 46 kWp capacity solar power plant construction project occurred in year 8 with a nominal net cash flow value of IDR 5,302,464.
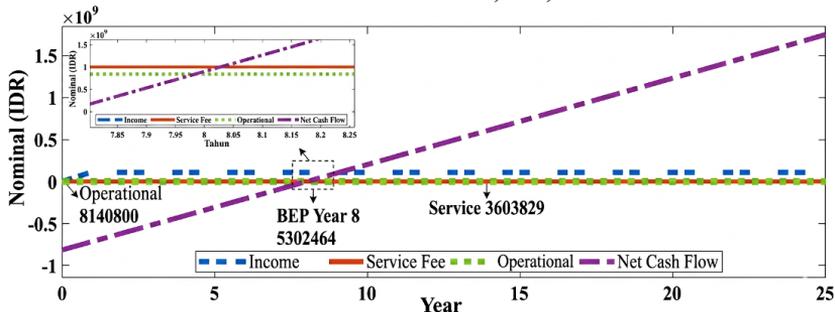

Fig. 14 – *Break Even Point.*

4.4.3 Return on Investment (ROI)

Based on the calculation using (17), the results obtained are represented in Fig. 15, where it can be seen in the graph that the ROI value in year 1 is still negative, which is –87% and ROI is negative until year 8, this happens because the amount of money available is not sufficient to cover the investment costs that have been made, then only in year 9 the ROI value is positive, which is 13%, meaning that in year 9 only get a profit of 13%. In the following year, the ROI percentage value increases until the 25th year, which is 215%, meaning that this project will benefit from the investment that has been made, which is 215% of the total investment that has been made.
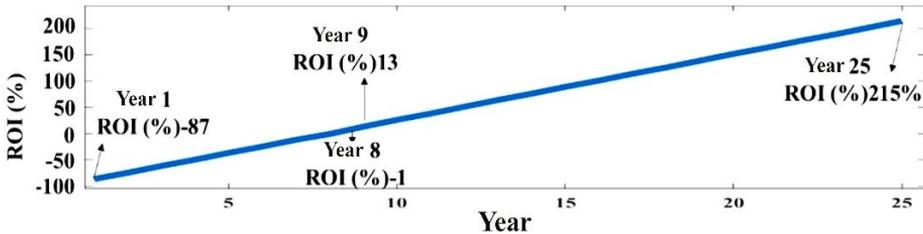

Fig. 15 – *Return on investment.*

The findings of this study align with previous research on hybrid solar power systems but show improvements in efficiency and financial feasibility. For example, a study by [9] on a 10 MW grid-connected solar plant reported a Performance Ratio (PR) of 72.3%, whereas this study achieved 75.7%, indicating better system efficiency. In terms of financial feasibility, [10] found a Payback Period of 10 years for a 50 MW system, while this study's 46 kWp system achieves a shorter Payback Period of 9 years with an ROI of 215%, making it a viable option for rural electrification.

In terms of environmental impact, [11] reported that an 80 kWp solar system reduced 1,500 tons of CO_2 over 25 years, while this study's 46 kWp system mitigates 1,118 tons of CO_2 in the same period. Although the total reduction is lower due to the system's smaller size, the CO_2 reduction per kWp is comparable, demonstrating the effectiveness of small-scale hybrid solar power plants in reducing carbon emissions. These results reinforce the feasibility of implementing such systems in off-grid and semi-grid rural communities in Indonesia.

The results of this study demonstrate that a 46 kWp hybrid solar power plant is a viable solution for rural electrification, with strong economic feasibility and environmental benefits. This methodology can be extended to other remote or off-grid areas in Indonesia, particularly in regions with similar solar radiation levels, such as Nusa Tenggara, Kalimantan, and Sulawesi. By scaling the system

to larger capacities (e.g., 100 kWp – 1 MWp), it could support industrial zones, educational institutions, or government-backed rural electrification programs. Additionally, integrating IoT-based monitoring and AI-driven predictive maintenance could further enhance system efficiency and operational reliability. Future implementations could also explore hybridization with other renewable sources, such as wind or micro-hydro power, to ensure a more stable energy supply in regions with intermittent solar radiation.

To further assess the financial robustness of this project, a sensitivity analysis was conducted by varying key economic parameters, including electricity price escalation, interest rates, and component costs. If electricity tariffs increase by 4% per year, the Payback Period (PP) shortens to 7.5 years, and the ROI increases to 240%, while stagnant electricity prices could extend the PP to 11 years. Changes in interest rates also impact financial feasibility, where an increase to 12% reduces NPV to IDR 350,000,000, whereas a lower rate of 6% improves it to IDR 450,000,000. Additionally, if solar panel costs increase by 15%, the PP extends to 10 years, but the project remains viable. Conversely, a 10% reduction in panel costs improves ROI to 230%, with a BEP in year 7. These findings highlight that the project is financially resilient to moderate economic fluctuations, making it a secure investment for expanding renewable energy access in rural and semi-urban areas.

5   Conclusion

This study demonstrates that a 46 kWp hybrid solar power plant is a viable and sustainable solution for rural electrification, offering both economic feasibility and environmental benefits. The system achieves a Performance Ratio (PR) of 75.7%, with a Net Present Value (NPV) of IDR 404,631,838, a Payback Period (PP) of 9 years, and a Return on Investment (ROI) of 215%. Additionally, this system contributes to reducing CO_2 emissions by 1,118 tons over 25 years, supporting SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Communities). These findings confirm the potential of hybrid PV systems to provide clean and cost-effective energy, particularly in off-grid and semi-grid rural areas.

Future research should explore the impact of shading and advanced solar tracking systems to further improve energy efficiency. Implementing adaptive MPPT algorithms, AI-driven predictive maintenance, and hybridization with other renewable sources (such as wind or micro-hydro power) could optimize system performance. Additionally, more comprehensive life-cycle cost analysis and real-world performance validation should be conducted to refine techno-economic models. Policymakers are encouraged to introduce incentives for small-scale solar hybrid systems, revise feed-in tariff policies to enhance financial attractiveness, and support R&D initiatives for advanced PV

technologies. Industry practitioners should consider integrating IoT-based monitoring and energy storage solutions to improve the reliability and scalability of solar power projects. By addressing these aspects, future developments in hybrid PV systems can accelerate the transition toward sustainable and resilient energy infrastructures.

6 Acknowledgments

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