

Design and Performance Evaluation of a Hybrid Photovoltaic System Integrated with Battery Storage and Utility Grid for Residential Applications

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ABSTRACT

The increasing demand for residential electricity requires a reliable and sustainable energy supply. However, photovoltaic (PV) systems are highly dependent on solar irradiance, resulting in fluctuating power generation. This study designs and evaluates a prototype hybrid PV system integrating a 160 Wp solar panel, a 12 V 100 Ah battery, a 1000 W hybrid inverter, and the utility grid (PLN). Performance was evaluated based on voltage, current, power, and irradiance. The results show that an average irradiance of 560.7 W/m² produced 15.91 V, 1.77 A, and 28.03 W, with a maximum power of 45.49 W at 754.9 W/m². The system maintained stable output voltage while current and power increased with irradiance, and it reliably supplied a daily load of 320 Wh using solar energy as the primary source, batteries for storage, and the grid as backup. These results demonstrate that the proposed hybrid PV system improves the reliability of residential electricity supply.



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1. INTRODUCTION

Electrical energy is essential for household activities, and demand continues to increase with population growth and technological development [1]. However, electricity generation is still dominated by fossil fuels, which have limited availability and contribute to environmental pollution. Therefore, renewable energy sources, particularly solar energy, have become an important alternative. Indonesia has strong potential for solar energy utilization due to its high solar irradiance throughout the year, making Solar Power Plants (PLTS) a promising solution for residential electricity supply [3], [4].

However, the independent implementation of solar power plants still faces several obstacles, particularly related to dependence on weather conditions [5]. In addition, high initial investment costs and limited daily energy production remain major challenges [1]. With PLN integration, electricity supply can be maintained when the power from solar panels and batteries is insufficient. Furthermore, the use of a hybrid system is more economical because it does not require a large battery capacity like an off-grid system. This system is also known to increase system reliability and flexibility in meeting electricity needs [6].

Previous studies have shown that hybrid photovoltaic (PV) systems can improve the reliability of electricity supply and reduce dependence on conventional energy sources. However, most existing

research focuses on simulation-based analysis or large-scale implementations, with limited experimental validation of residential-scale hybrid PV prototypes under actual operating conditions. Therefore, this study aims to design, develop, and experimentally evaluate a residential-scale hybrid PV system integrated with a battery, a hybrid inverter, and the utility grid (PLN). The system performance is assessed based on solar irradiance, voltage, current, and power characteristics to evaluate its operational reliability and effectiveness in providing a continuous electricity supply. The findings are expected to provide practical insights into the implementation of residential hybrid PV systems and support the broader adoption of renewable energy in line with national energy development policies [2].

2. RESEARCH METHOD

The research method is used in designing a prototype hybrid solar power plant (PLTS) system with the PLN. The research method is structured systematically according to the stages shown in Figure 1.

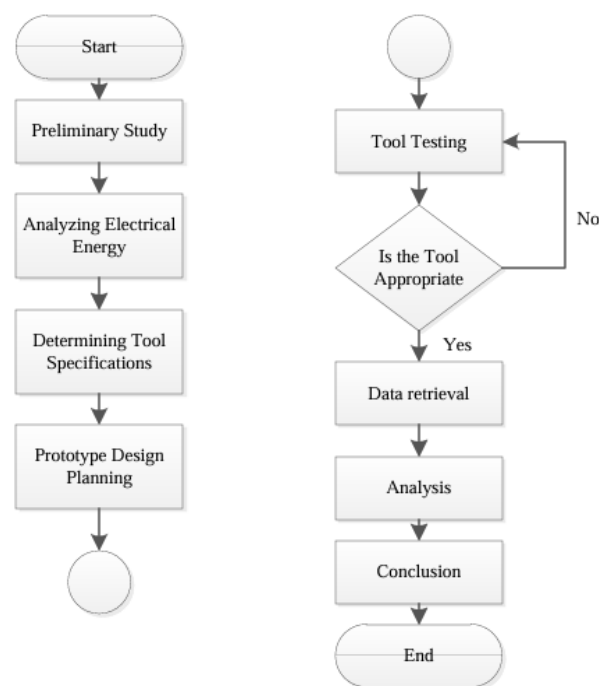


Figure 1. Research flowchart of the hybrid PLTS prototype system

Based on Figure 1, the research began with a preliminary study and analysis of the electrical energy requirements to determine the system capacity. The main components, including the solar panels, battery, and inverter, were then selected, followed by the design and implementation of the hybrid PV prototype. System performance was evaluated by measuring voltage, current, and power under actual operating conditions. Finally, the collected data were analyzed to assess the overall system performance, and conclusions were drawn based on the experimental results.

2.1. Planning

A hybrid solar power plant (PV) system integrated with the utility grid (PLN) was designed to meet residential electricity demand by utilizing solar panels as the primary energy source, batteries for energy storage, and the utility grid as a backup to ensure a continuous power supply. As shown in Figure 2, the system configuration was developed by first analyzing the household electrical load to determine the daily energy consumption (kWh/day), which served as the basis for sizing the solar panels and battery according to the calculated energy demand. [7].



Figure 2. Prototype Components of the Hybrid Solar Power System

The research methodology included energy demand analysis, component selection, prototype implementation, and system testing. Household energy consumption was analyzed to determine the capacities of the PV panels, battery, and hybrid inverter. The prototype was tested at Universitas Trisakti, Jakarta Barat, Indonesia, on December 17–19, 2025, from 10:00 AM to 2:00 PM at 20-minute intervals. System performance was evaluated based on solar irradiance, voltage, current, power output, and load supply capability. Figure 3 illustrates the proposed hybrid PV system, where the solar panels and battery are connected to a hybrid inverter that supplies power to household loads. The inverter is also connected to the PLN grid as a backup source [10].

The system prioritizes energy from the PV panels, followed by the battery, and finally the utility grid when required. The household load used for system sizing is presented in Table 1.

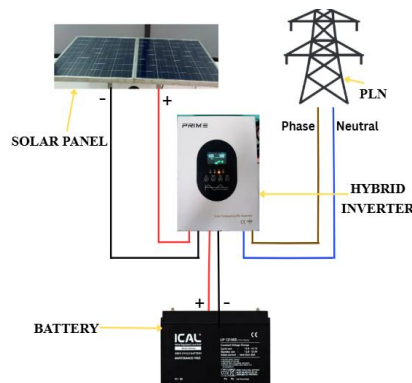


Figure 3. Configuration of the proposed hybrid solar power system

Table 1. Loads

No	Load	Unit	Watt	Time	Watt/hour	Info
1	Lamp	3	3 W	10 h	90 Wh	Room
2	Fan	1	25 W	4 h	100 Wh	Bedroom
3	Electric Socket	1	65 W	2 h	130 Wh	HP, Laptop
Total			99 W		320 Wh	

Figure 4 shows that household electricity consumption is predominantly at night, so a hybrid solar PV system with PLN (State Electricity Company) needs to be supported by adequate battery capacity to meet the load demand when solar energy is not available [11].

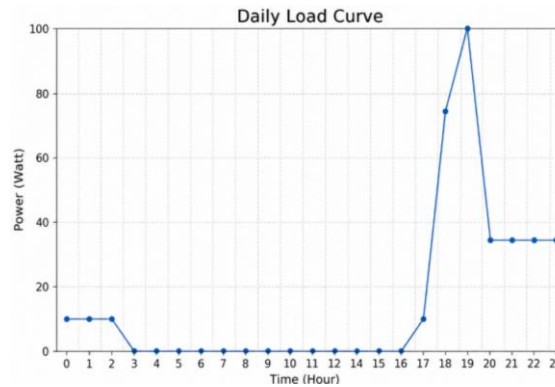


Figure 4. Daily Loads Curve

Therefore, the total daily energy requirement is:

$$E_{total} (Wh) = 320 Wh$$

Before implementation, calculations are made regarding the required component capacity. The calculations are as follows:

1. Solar Panel Capacity Calculation

The solar panels must be capable of producing 320 Wh of energy per day. Assuming an average of 4 hours of effective sunlight per day, the calculation based on equation 1 for the panel capacity is [12]:

$$P_{panel} (Wp) = \frac{E_{daily}}{T_{sun}} = \frac{320 Wh}{4 hours} = 80 Wp \quad (1)$$

Considering system losses, including cable losses, inverter efficiency, and a safety factor for variations in solar irradiance, two 80 Wp solar panels were selected for the prototype. This configuration provides additional capacity to improve energy generation reliability and support battery charging under non-optimal irradiation conditions.

2. Solar Charge Controller Capacity Calculation

The SCC is used to regulate the current and voltage from the panel to the battery. The SCC capacity is determined based on equation 2 and the output of the solar panel [12]:

$$SCC(A) = \frac{P_{panel}}{V_{system}} = \frac{80 Wp}{12 V} = 6.6 A \quad (2)$$

Use an SCC with a minimum current of 10A.

3. Inverter Capacity Calculation

An inverter is used to convert the 12 V DC battery output into 220 V AC for household loads. Although the maximum simultaneous load is 99 W, a 1000 W Pure Sine Wave inverter was selected to accommodate efficiency losses, inductive load starting currents, and future system expansion, ensuring reliable system operation.

4. Battery Capacity Calculation

Batteries are used to store energy from solar panels and supply the load when there is no sunlight. Battery capacity can be calculated using equation 3 as follows [12]:

$$Capacity(Ah) = \frac{E_{total}}{V_{system}} = \frac{320 Wh}{12 V} = 6.6 A \quad (3)$$

A 12 V 100 Ah VRLA battery was selected, providing a theoretical storage capacity of approximately 1200 Wh. However, the actual usable energy is lower due to the battery DoD, inverter efficiency, and safe operating limits. Therefore, the selected battery capacity is sufficient for the designed load while maintaining battery reliability.

2.2. Testing

To evaluate the hybrid PV system performance, tests were conducted on the solar panel, battery, hybrid inverter, and household load. Solar irradiance was measured using a solar power meter, while

voltage and current were measured using a digital multimeter. The PV module was tested under outdoor conditions, and the load used was based on the household load listed in Table 1.

Solar Panel Output Testing, this test is conducted to ensure that the solar panels are capable of producing DC voltage and current according to specifications [7]. Measurements are taken during daylight hours with optimal sunlight intensity using a digital multimeter. The parameters observed include the panel's voltage (V), current (A), and power output (W).

Inverter Performance Testing, inverter testing aims to evaluate the power conversion from direct current (DC) to alternating current (AC), as well as the automatic switching function between solar panels, batteries, and the electricity grid. Testing is carried out by monitoring the AC output voltage (220V), frequency stability (50Hz), and inverter response when the main power source (panel) is unavailable.

Household Load Supply Testing, this test was conducted by connecting household electrical loads directly to the system. The loads included LED lights, televisions, and mini fans. The goal was to ensure the system could supply the loads stably, without voltage disruptions or sudden power outages. Observed parameters included voltage stability and the system's ability to maintain energy supply within the inverter's capacity.

2.3. Component List

Component selection is based on system requirements and their functions for use in designing a hybrid solar power system with PLN. The specifications of each component are based on the calculations used as the basis for system design, as shown in Table 2.

Table 2. Specifications component

No	Component	Unit	Specification	Function
1	Solar Panel	2	80Wp, 16V	Source from PLTS
2	Battery VRLA	1	12V, 100Ah	Saving Energy
3	Inverter Hybrid	1	1000W, 12VDC to 220VAC	DC to AC for Loads

3. RESULTS AND DISCUSSION

This section presents the implementation of the hybrid PV system with PLN, including the experimental results and performance analysis. The system performance was evaluated based on PV panel and inverter testing through measured voltage, current, power, and irradiance data. The analysis includes comparisons of daily performance variations, the effect of irradiance on power output, and the system capability in supplying the load.

3.1. Design Result

Based on the design, the system developed is a hybrid solar power system that combines energy sources from solar panels, batteries, and the PLN grid with a hybrid inverter, as shown in Figure 5.

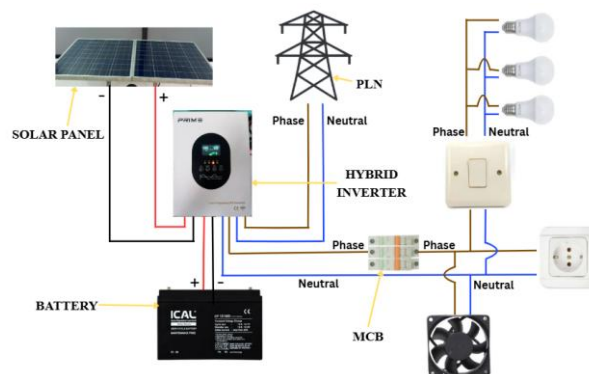


Figure 5. Design of the hybrid solar power system

Based on Figure 5, this hybrid solar power system has met the criteria for testing. All major

components have been properly integrated, including the solar panels, hybrid inverter, battery, PLN power source, and load. The configuration and interconnections between components in the hybrid solar power system with PLN implemented in this study can be seen in Figure 6.

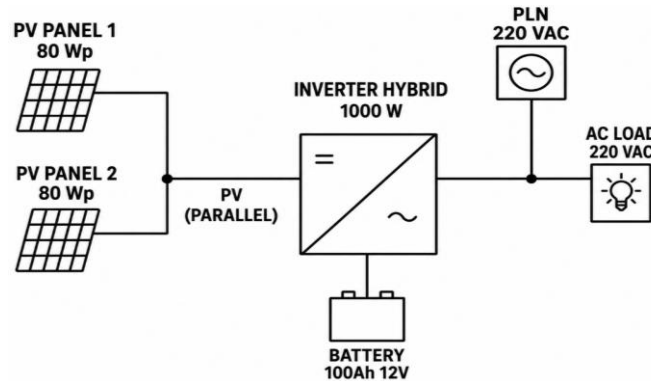


Figure 6. Single-Line diagram of the proposed hybrid solar power system

Therefore, this system is ready for performance testing, which includes testing the solar panel output, testing the performance of the hybrid inverter, and evaluating the system's ability to supply the load under various operating conditions.

3.2. Test Result

1. Solar Panel Output Testing

The solar panel output was measured over three days. Test results are presented in Table 3.

Table 3. Output solar panel first day

Time	W/m^2	V	A	W
10.00	285.4	15.91	0.65	10.34
10.20	334.3	16.18	0.72	11.65
10.40	294.6	16.19	0.62	10.04
11.00	423.9	16.41	1.12	18.38
11.20	620.8	16.18	1.26	20.39
11.40	637.7	16.36	1.62	26.50
12.00	721.5	15.96	2.85	45.49
12.20	754.9	14.82	2.56	37.94
12.40	702.3	14.91	2.67	39.81
13.00	668.4	16.87	2.45	41.33
13.20	615.7	15.91	2.51	39.93
13.40	642.1	15.62	2.41	37.64
14.00	587.4	15.53	1.61	25.00
Average	560.7	15.91	1.77	28.03

Based on Tables 3 and 4, the PV panel performance was strongly influenced by solar irradiance and weather conditions. On the first day, a maximum irradiance of 754.9 W/m^2 produced a stable voltage of 14.82–16.87 V (average 15.91 V), with a maximum current of 2.85 A, maximum power of 45.49 W, and average outputs of 1.77 A and 28.03 W. On the second day, cloudy weather and light drizzle reduced the maximum irradiance to 435.2 W/m^2 , resulting in a stable voltage of 12.43–16.42 V (average 14.59 V), a maximum current of 1.92 A, maximum power of 29.03 W, and average outputs of 0.93 A and 13.66 W. These results indicate that higher irradiance increases the PV panel current and power output, while the output voltage remains relatively stable.

Table 4. Output solar panel second day

Time	W/m^2	V	A	W
10.00	200.8	12.43	0.91	11.31
10.20	218.8	14.31	1.02	14.60
10.40	210.4	12.93	0.42	5.43
11.00	227.3	15.26	0.67	10.22
11.20	243.9	13.84	0.48	6.64
11.40	252.2	15.29	0.82	12.54
12.00	278.5	16.42	0.92	15.11
12.20	313.2	15.01	1.12	16.81
12.40	348.8	15.69	1.85	29.03
13.00	392.2	14.04	1.92	26.96
13.20	435.2	15.47	0.82	12.69
13.40	243.8	15.49	0.64	9.91
14.00	182.6	13.53	0.47	6.36
Average	272.9	14.59	0.93	13.66

The third-day results show that irradiance gradually increased to a maximum of 624.2 W/m^2 at 1:20 PM before decreasing. The solar panel output voltage remained relatively stable between 14.82–16.36 V, with an average of 15.68 V. The output current reached a maximum of 2.39 A at 1:00 PM, while the output power ranged from 5.04 W to 36.95 W. These results indicate that higher irradiance increases the solar panel output current and power, whereas the voltage remains relatively stable. The third-day results are presented in Table 5.

Table 5. Output solar panel third day

Time	W/m^2	V	A	W
10.00	218.3	15.91	0.66	10.50
10.20	235.8	16.19	0.91	14.73
10.40	252.2	16.18	0.89	14.40
11.00	269.6	16.36	0.91	14.89
11.20	295.4	15.96	1.32	21.07
11.40	330.9	15.25	1.01	15.40
12.00	408.9	14.82	0.34	5.04
12.20	443.6	14.91	1.67	24.90
12.40	478.3	15.68	1.93	30.26
13.00	538.3	15.46	2.39	36.95
13.20	624.2	15.62	1.68	26.24
13.40	606.5	15.95	1.20	19.14
14.00	496.6	15.53	1.14	17.70
Average	397.8	15.68	1.23	19.33

Overall, the average irradiance value of 397.8 W/m^2 resulted in an average voltage of 15.68 V, an average current of 1.23 A, and an average power of 19.33 W. These results it can be concluded that irradiance remains the dominant factor influencing the current and power output of the solar panel, while the voltage remained relatively stable in response to changes in solar radiation intensity.

2. Hybrid Inverter Output Testing

In this testing phase, the hybrid inverter is connected to a battery, with the inverter's input power coming from the battery's output. The test results can be seen in Table 6.

Table 6. Output Hybrid Inverter

Time	V	A	W
19.00	209.5	0.14	29.33
19.20	209.7	0.17	35.65
19.40	209.4	0.19	39.79
20.00	209.8	0.31	65.04
20.20	209.6	0.27	56.59
20.40	209.9	0.34	71.37
21.00	210.1	0.41	86.14
21.20	210.2	0.43	90.39
21.40	210.1	0.36	75.64
22.00	210.3	0.38	79.91
22.20	210.2	0.31	65.16
22.40	210.4	0.26	54.70
23.00	210.1	0.22	46.22
Average	209.95	0.29	61.23

3.3. Analysis of Results

This section presents the results of testing conducted using manual measurements from 10:00 AM to 2:00 PM WIB, with data collected every 20 minutes for three days.

1. Solar Panel Voltage Output Analysis

In this analysis, researchers tested the solar panel's output voltage. The test results are in Figure 7.

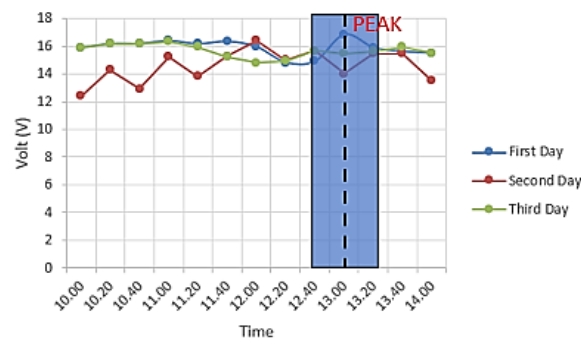


Figure 7. Comparison of solar panel output voltage during peak hours

2. Solar Panel Current Output Analysis

In this section, we analyze the solar panel output current to determine the amount of current generated by the system. The results of the analysis are presented in Figure 8. Figure 8 shows that the output current varied more significantly than the voltage. On the first day, the current reached a maximum of approximately 2.8 A at around 12:00 PM before decreasing. On the second day, the peak current was lower, at approximately 2.0 A, due to cloudy weather and drizzle. On the third day, the current increased to approximately 2.4 A at around 1:00 PM.

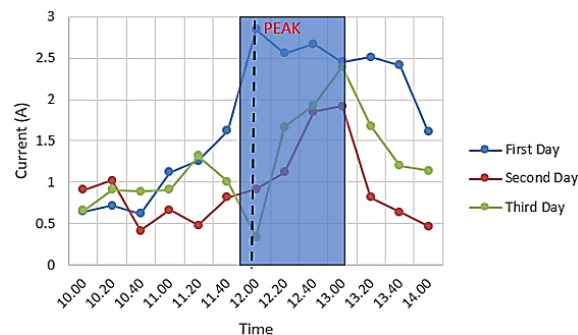


Figure 8. Comparison of solar panel output current during peak hours

These results indicate that the solar panel output current is strongly influenced by solar irradiance and weather conditions.

3. Solar Panel Power Output Analysis

This analysis discusses the solar panel output power to determine the amount of power generated by the system. The results of the analysis are as follows.

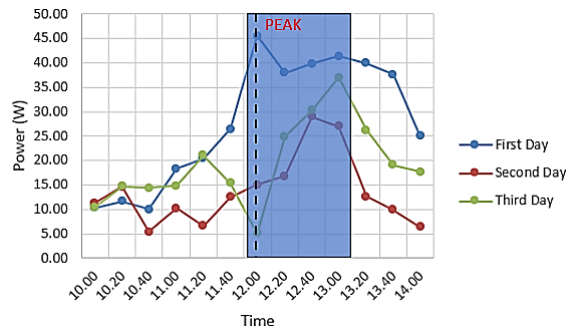


Figure 9. Comparison of solar panel output power during peak hours

Figure 9 shows that the output power follows the same trend as the output current. On the first day, the output power gradually increased and reached the highest value of approximately 45 W at around 12:00 PM before decreasing in the afternoon. On the second day, the maximum power was lower, at approximately 29 W, due to reduced irradiance caused by cloud cover and light rainfall. On the third day, the output power reached approximately 37 W at around 1:00 PM, which was higher than the second day but lower than the first day. These results indicate that the solar panel output power is strongly influenced by variations in solar irradiance.

4. Irradiance and Output Power

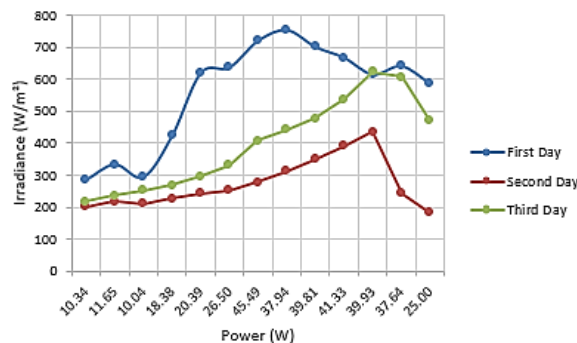


Figure 10. Relationship between irradiance and output power

Overall, the results show that current and power are strongly affected by solar radiation, while voltage remains relatively stable. Variations across the three test days indicate that weather conditions, especially cloud cover and sky clarity, significantly influence solar panel performance.

5. Inverter Output Analysis

The test results showed that the hybrid inverter maintained a stable output voltage of 209.4–210.4 V with an average of 209.95 V despite load variations. The output current increased from 0.14–0.19 A with three lamps to a maximum of 0.43 A when additional charging loads were connected. These results indicate that the inverter was able to maintain voltage stability and provide reliable power for household loads.

6. Battery Charging Time

To calculate the time to fully charge the battery, use equation 3 [12]:

$$\text{Battery Power} = 1200\text{Wh}$$

$$\text{Apparent solar panel power (Highest)} = 80\text{ Wp}$$

$$\text{Battery Charging Time} = \frac{1200 \text{ Wh}}{80 \text{ Wp}} = 15 \text{ Hours}$$

In this calculation, the apparent solar panel power is obtained from measurements over three days. To fully charge the battery, with a 12V 100Ah battery capacity that can power the load for four days, the charging time is 15 hours.

7. Operational Efficiency of the PV Module During Field Testing

Efficiency data is calculated using test results from the first day, when conditions were relatively bright and slightly cloudy. Therefore, to find this value, the solar panel area is first measured using equation 4 [11]:

$$A = p \times l = 0.998 \times 0.664 = 0.66 \text{ m}^2 \times 2 (\text{Panels}) = 1.32 \text{ m}^2 \quad (4)$$

Therefore, to determine P_{in} (watts), use equation 5 as follows [11]:

$$P_{in} = G \times A = 560.7 \times 1.32 = 740.1 \text{ W} \quad (5)$$

Therefore, to determine P_{out} (watts), use equation 6 as follows [11]:

$$P_{out} = V \times I = 15.91 \text{ V} \times 1.77 \text{ A} = 28.2 \text{ W} \quad (6)$$

Therefore, the efficiency of the solar power plant can be calculated based on equation 7 as follows [11]:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{28.2}{740.1} \times 100\% = 3.8\% \quad (7)$$

Based on the measured irradiance, panel area, and output power, the operational efficiency of the PV module was calculated at 3.8%. This value is lower than the typical rated efficiency of commercial PV modules (18–24%) because it represents real outdoor operating conditions. The reduced efficiency was mainly affected by lower irradiance, module temperature, fixed panel orientation, and electrical losses in the system.

8. Overall Analysis

This section analyzes the hybrid PV system based on experimental results. The solar panel supplies the load and charges the battery during the day, while PLN provides backup power when needed. The hybrid inverter manages the energy sources to maintain continuous operation in Table 7.

Table 7. Performance specifications of system components

Component	Parameter	Spec	Result
Solar Panel	V	16 V	15.91 V
	A	5 A	2.85 A
	W	80 W	45.49 W
Hybrid Inverter	V	220 V	210.4 V
	A	40 A	0.43 A
	W	1000 W	90.39 W
	F	50 Hz	50 Hz

Based on Table 7, the hybrid solar PV system demonstrated satisfactory performance in supplying the load, although some parameters did not reach the planned targets. The solar panel voltage of 15.91 V was close to the target of 16 V, while the current and power outputs of 2.85 A and 45.49 W were lower due to variations in weather conditions, solar irradiance, and the angle of sunlight during testing.

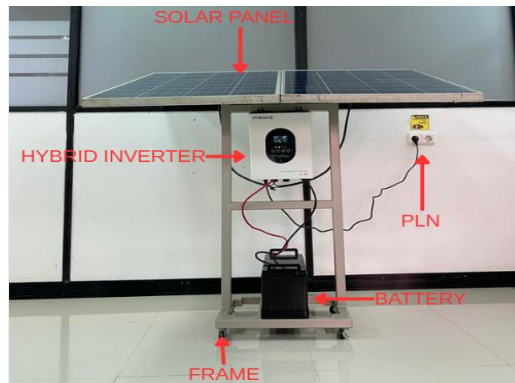


Figure 11. Prototype of the proposed hybrid solar power system

Figure 11 demonstrates that the hybrid PV system effectively stored solar energy during the day and supplied power at night with PLN as backup. The inverter maintained a stable 210.4 V, 50 Hz output and supplied 320 Wh of daily energy, showing potential for residential use.

4. CONCLUSION

This study successfully developed a hybrid PV system prototype consisting of a 160 Wp solar panel, 12 V 100 Ah battery, 1000 W hybrid inverter, and PLN backup. The system supplied a 320 Wh daily load, with solar energy as the primary source and battery storage for energy management. The results show that PV performance is affected by solar irradiance, while the inverter provides stable AC output and automatic source switching. Future work should focus on optimizing panel orientation, MPPT performance, and long-term system evaluation.

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