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Design and Construction of Off-Grid PLTS Installation in a Smart Home

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Abstract— **The increasing demand for household electrical energy continues to grow along with the widespread use of electronic devices and the development of smart home technologies. However, the availability of electrical power from conventional energy sources is not always sufficient to meet these demands sustainably. One potential solution is the utilization of an off-grid Solar Power Plant (PLTS off-grid) system that can operate independently without reliance on the public electricity grid. This research aims to design and construct an off-grid solar power installation integrated into a smart home system and to measure the performance of the generated electrical power. The proposed system consists of solar panels, a Maximum Power Point Tracking (MPPT) controller, batteries, an inverter, an Automatic Transfer Switch (ATS), and a WiFi-based smart MCB. The research methodology includes system design, component installation, and direct performance testing through electrical parameter measurements. The results indicate that optimal system performance occurs during midday, between 11:00 and 14:00, with the solar panel current reaching 31.6 Amperes, panel voltage of 78 Volts, and battery voltage of 54.4 Volts. In the afternoon, between 15:30 and 17:00, system performance decreases due to reduced solar irradiance. Furthermore, five-day air conditioner energy consumption data show that the off-grid solar power system is capable of meeting household electrical energy needs, with a total energy output of 9.222 kWh. These results demonstrate that the installation and power measurement of the off-grid solar power system were successfully implemented, and that electrical energy production is strongly influenced by solar irradiance intensity.**

Keywords— Off-grid solar power system, solar panel, maximum power point tracking, smart home, power monitoring.

I. Introduction

Solar power plants generate electrical energy by converting photons from sunlight into usable electrical power through photovoltaic cells. Solar panels consist of multiple solar cell modules capable of absorbing solar radiation and transforming it into electrical energy for daily household applications [1]. This technology has gained increasing attention due to its renewable nature and its potential to reduce dependence on fossil-based energy sources.

The demand for electrical power in the household sector continues to increase along with the growing use of electronic devices in daily life. Dependence on conventional energy sources such as the national electricity grid creates challenges related to cost efficiency and long-term sustainability [2]. As electricity consumption rises, alternative energy solutions are required to ensure reliable and environmentally friendly power supply.

One solution that has been widely developed is the utilization of Solar Power Plants (PLTS), particularly off-grid systems that operate independently without relying on the main electricity network [3]. Off-grid PLTS systems utilize solar panels as the primary energy source and batteries as energy storage, enabling continuous power supply for household needs. Previous studies have shown that such systems are efficient and suitable for residential applications in various regions [4].

In addition to energy efficiency and sustainability, off-grid PLTS systems have the potential to support smart home environments by enabling integrated and autonomous energy management [5]. A key element of the smart home concept is the ability to monitor, manage, and optimize energy consumption in real time. In this study, a WiFi-based smart MCB integrated with the Tuya Smart application serves as the intelligent energy management interface, allowing users to remotely monitor load status, track daily consumption, and receive real-time data on energy usage. This IoT-based monitoring capability constitutes a fundamental smart home feature, enabling data-driven energy decisions and laying the foundation for future automation and adaptive load control.

Therefore, this study focuses on the design and implementation of an off-grid PLTS installation integrated with a smart home monitoring system based on a WiFi-enabled smart MCB. The research covers system design, component configuration, performance measurement, and IoT-based energy monitoring — all of which collectively constitute a practical smart home energy management implementation. The results are expected to demonstrate that an off-grid PLTS system, when integrated with real-time monitoring and remote-control capabilities, can serve as a reliable and intelligent primary energy source for modern smart homes.

II. Research Methodology

A. Data Collection Techniques

The data collection techniques used in this study are as follows:

1. Direct Observation

Direct observation was conducted during the installation process of the off-grid solar power system, including the mounting of solar panels, electrical wiring, and system configuration. This method was used to ensure that all components were installed according to the design specifications.

2. Electrical Power Measurement

An MPPT (Maximum Power Point Tracking) controller was installed to measure the electrical power generated and stored daily by the solar panels. The measured parameters include current, voltage, and energy production.

3. Real-Time Monitoring via Application

Real-time monitoring of the electrical system was performed using a smart MCB integrated with a WiFi-based application. The monitored data include load usage status and historical energy consumption, which are used to analyze system performance and efficiency.

To evaluate the performance of the off-grid solar power system in converting solar energy into household electrical loads, an energy efficiency analysis was conducted in Chapter IV. The efficiency was calculated based on the comparison between input energy (DC from solar panels) and output energy (AC supplied to household loads), using the following equation:

$$Efficiency = \frac{Output\ Energy\ (kWh)}{Input\ Energy\ (kWh)} \times 100\% \qquad (1)$$

B. Hardware System Design

The hardware design of the solar power installation was developed to clearly visualize the workflow and interconnection between system components, as illustrated in the block diagram shown in Figure 1.

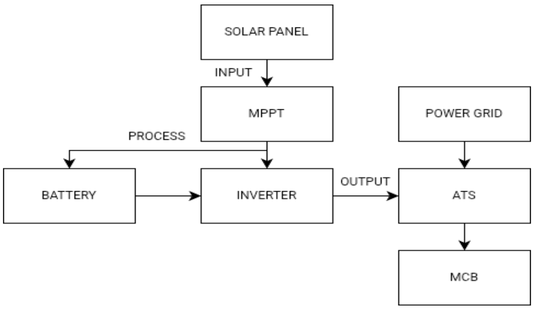

Figure 1. Block Diagram of the Off-Grid Solar Power System

Based on the block diagram, the system operates by converting solar energy into electrical energy using solar panels. The generated power is then delivered to the MPPT controller to regulate and optimize energy harvesting. The energy from the MPPT is used to charge the battery as a storage medium and can also be supplied directly to the inverter. The inverter converts direct current (DC) from the battery into alternating current (AC) suitable for household use.

The AC output from the inverter is connected to an Automatic Transfer Switch (ATS), which functions to automatically select the power source between the solar power system and the public utility grid (PLN), depending on power availability. When solar power is sufficient, the system prioritizes PLTS energy; otherwise, it switches to PLN power. The selected power source is then distributed through a Miniature Circuit Breaker (MCB) as the final protection before supplying household loads.

C. System Design Procedure

The system design procedure used in this research consists of the following stages:

1. Needs Analysis, identifying system requirements and electrical load demands for the smart home application.
2. Conceptual Design, developing the initial concept and configuration of the off-grid solar power system.
3. Testing and Validation system to ensure proper operation and maximum performance in meeting household energy needs.
4. Installation Technique, the installation of solar panels requires careful planning and execution to ensure optimal and safe operation. In this study, four solar panels were connected using a series–parallel

configuration. Series connections were made by connecting the positive (+) MC4 connector of one panel to the negative (–) MC4 connector of another panel. Two series-connected panels were then connected in parallel before being connected to the MPPT controller.

D. *Power Production Monitoring of Solar Panel*

Monitoring of solar panel power production was conducted directly through the MPPT controller. The MPPT digital display presents real-time output data, including current, voltage, and total energy generated by the solar panels.

Figure 2. Display DC Power Production Monitoring on MPPT

E. *AC Output Power Monitoring from the Inverter*

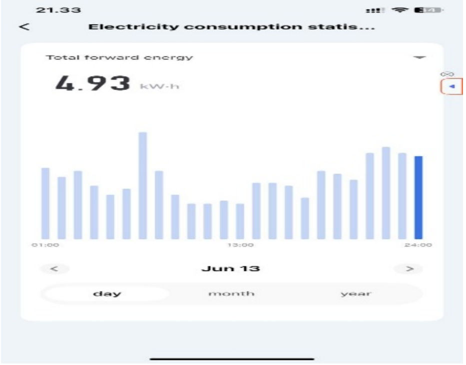

Figure 3. AC Power Monitoring Display via Tuya Application

Monitoring of the inverter’s AC output power was performed using a smart MCB integrated with the Tuya Smart application. Through this application, users can monitor real-time household electricity consumption, including daily energy usage from loads connected to the solar power system. The application displays total energy consumption data, facilitating analysis of system efficiency and energy usage patterns.

F. *Research Flowchart*

The research workflow is illustrated in the flowchart shown in Figure 4.

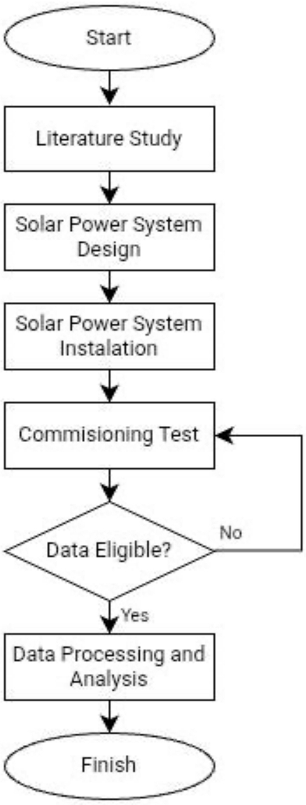

Figure 4. Research Flowchart

G. *Data Analysis*

The data analysis in this study includes:

1. Analysis of electrical power generated by the off-grid solar power system, including solar panel current, panel voltage, and battery voltage.
2. Monitoring and analysis of energy consumption supplied by the solar power system through the smart MCB.

III. Results and Discussion

A. *Reseacrh Results*

1. Wiring Diagram of the Off-Grid PV System

Figure 5 illustrates the wiring diagram of the off-grid photovoltaic (PV) system implemented in this study. The system consists of several main components that work together to convert solar energy into usable electrical energy for household loads.

The solar panels function as the primary energy source by converting solar irradiance into direct current (DC) electricity. The Maximum Power Point Tracking (MPPT) controller regulates and optimizes the power generated by the solar panels to ensure operation at the maximum power point. Electrical energy from the MPPT is directed to a $LiFePO_4$ battery, which serves as the energy storage medium. The inverter converts the stored DC power into alternating current (AC), enabling its use by household electrical appliances.

An Automatic Transfer Switch (ATS) is employed to automatically select the power source between the PV system (via the inverter) and the public electricity grid (PLN), depending on power availability. If the PV system cannot supply sufficient power, the ATS switches the load to the PLN. A smart MCB is installed as the final protection device, providing overcurrent protection and enabling real-time monitoring and remote control through a mobile application. Household electrical loads, such as lighting, fans, refrigerators, and other appliances, act as the final energy consumers.

Overall, this wiring configuration enables the system to operate automatically, safely, and efficiently, while maintaining grid connectivity as a backup power source.

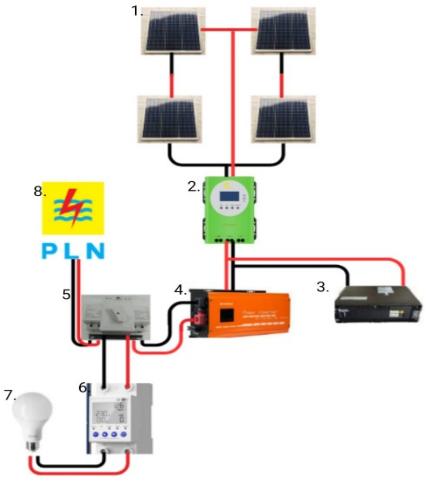

Figure 5. Wiring Diagram

2. House Layout and Solar Panel Installation

Figure 6 presents the house layout integrated with the solar panel installation. The solar panels are installed on the rooftop to maximize exposure to sunlight throughout the day. Near the front terrace area, a dedicated space is provided for housing system components such as the MPPT controller, battery, inverter, and protection devices. This configuration minimizes cable losses and simplifies maintenance.

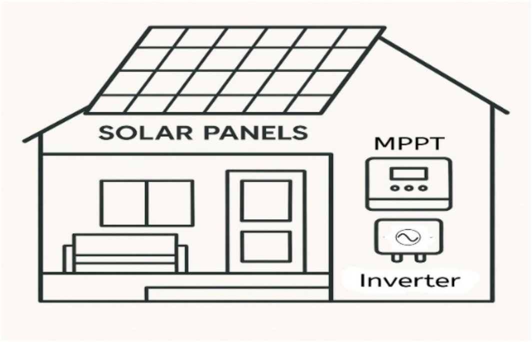

Figure 6. House Layout

The system utilizes four solar panels, each with dimensions of 2.4 m × 1.3 m and a rated capacity of 665 Wp. The panels are installed using a series-parallel configuration on the rooftop. Each panel has a nominal voltage of approximately 38.4 V and a current of 17.32 A, based on the specifications of the 60 A MPPT controller and a 48 V battery system. Figure 7 shows the physical dimensions of the solar panels used in this study.

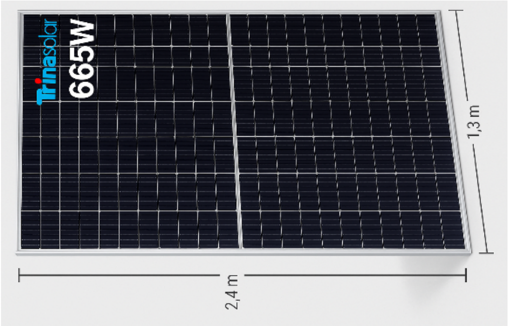

Figure 7. Dimension Solar Panels

3. 3. PV System Capacity and Configuration Analysis

To achieve the targeted system capacity, the off-grid PV system specifications are defined as follows:

- Number of solar panels: 4 units
- Rated power per panel: 665 Wp
- Voltage at maximum power (Vmp): ±38.4 V
- Current at maximum power (Imp): ±17.32 A

The panels are configured in a 2-series, 2-parallel (2S2P) arrangement. In the series configuration, two panels are connected to produce a maximum voltage of 76.8 V, while the current remains at 17.32 A. The two series strings are then connected in parallel, resulting in a total maximum current of 34.64 A while maintaining the same voltage level.

The total maximum power of the PV array is:

$$4 \times 665\ \mathrm{Wp} = 2{,}660\ \mathrm{Wp}\ (2.66\ \mathrm{kWp})$$

Because the PV array output voltage reaches approximately 76.8 V, an MPPT controller is required to regulate the voltage and convert it to a suitable 48 V charging voltage for the battery system. The battery used in this system has a capacity of 48 V and 100 Ah, corresponding to a total stored energy of 4.8 kWh. Considering an overall charging efficiency of approximately 85% (including MPPT, cabling, and battery losses), the effective energy required to fully charge the battery is approximately 5.65 kWh.

Under typical Indonesian solar conditions, with an average of 4–5 peak sun hours per day, the estimated daily energy production is:

$$2.66\ \mathrm{kWp} \times 4\ \mathrm{hours} = 10.64\ \mathrm{kWh/day}$$

Based on this value, the estimated time required to fully charge the battery under clear weather conditions is approximately 2.1hours. The series-parallel configuration is therefore selected to match the electrical characteristics of the MPPT controller and the battery system.

4. Daily Performance Analysis Based on DC Production Data

Table 1. MPPT DC Electrical Data for Off-Grid Solar Power System

No	Time	Current (A)	PV Voltage (V)	Battery Voltage (V)
1	08:24	14,5	60	48,5
2	09:01	21,6	74	49,1
3	10:05	27,8	68	50
4	11:04	31,6	64	50,4
5	12:26	23,8	68	50,8
6	13:23	11,9	78	54,4
7	14:27	12,2	77	54,4
8	15:21	4,5	80	53,2
9	16:06	6,1	80	53,2
10	16:31	8,4	70	50,3
11	17:16	2,2	58	49,5
12	17:56	0,4	67	49,5

Daily performance measurements were conducted on 15 June 2025 by recording DC current, panel voltage, and battery voltage at the MPPT controller. The measurement results are presented in Table 1.

The data indicate that system operation begins in the morning at 08:24, with a current of 14.5 A, panel voltage of 60 V, and battery voltage of 48.5 V, representing the initial charging phase. As solar irradiance increases, the current rises steadily, reaching a peak value of 31.6 A at 11:04. This period corresponds to the highest power production during the day.

After midday, the current gradually decreases due to reduced solar intensity and battery charge regulation by the MPPT. By late afternoon (17:56), the current drops to 0.4 A, indicating minimal power generation and a transition to battery discharge mode.

5. Analysis of PV Current & Analysis of PV Voltage

The PV current profile shows a clear dependence on solar irradiance. The current increases from 14.5 A in the morning to a maximum of 31.6 A around 11:04, which represents the optimal operating period of the system. After this peak, the current decreases gradually and approaches zero near sunset. This pattern aligns with the theoretical behavior of PV systems under daily solar radiation cycles.

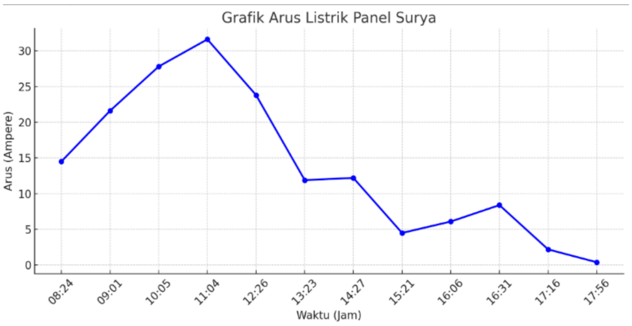

Figure 8. Solar Panel Current Graph

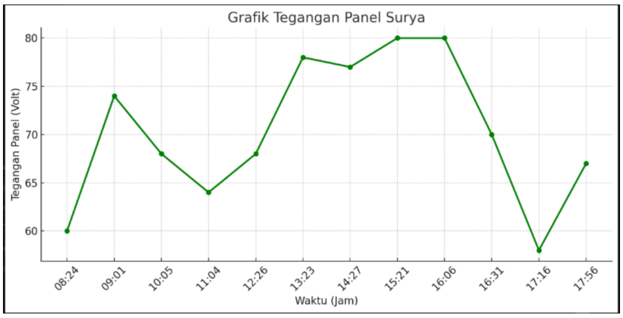

Figure 9. Solar Panel Voltage Graph

The PV voltage varies dynamically throughout the day due to changes in irradiance, temperature, and MPPT operating conditions. The voltage increases from 60 V in the morning to values between 78–80 V during peak sunlight hours, before decreasing toward the evening. These fluctuations demonstrate that the MPPT controller effectively maintains system stability while optimizing power output.

6. Battery Voltage Analysis

Battery voltage measurements indicate a gradual increase from 48.5 V in the morning to a maximum of 54.4 V between 13:23 and 14:27, confirming effective charging during peak solar hours. After this period, the voltage decreases gradually as the system transitions to supplying energy to household loads. The observed voltage range remains within the safe operating limits of the $LiFePO_4$ battery.

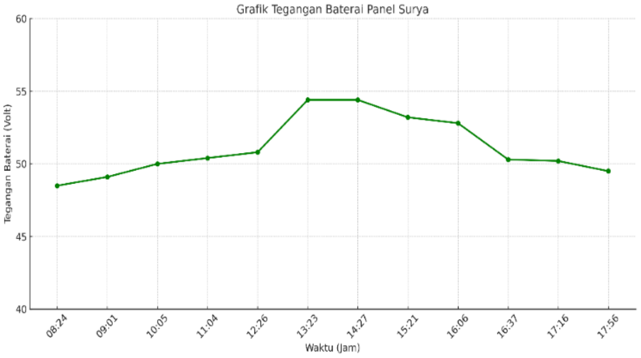

Figure 10. Battery Voltage Graph

B. Discussion

Energy production and consumption data were recorded over five days (10–14June 2025) using the MPPT controller and Smart MCB. Table 2 summarizes the daily DC energy generated by the PV system and the AC energy consumed by household loads.

Table 2 AC MCB measurement data

No	Date	DC Panel Energy (kWh)	AC Load (kWh)
1	10 june	6.455	5.96
2	11 june	6.495	4.93
3	12 june	9.222	6.4
4	13 june	7.156	5.98
5	14 june	5.148	5.48

For most observation days, the energy generated by the PV system exceeded household consumption, indicating that the system was capable of supplying daily energy demands independently. On 14 June, PV production was slightly lower than consumption; however, the energy deficit was compensated by the battery storage, ensuring uninterrupted power supply.

System efficiency was calculated by comparing AC load energy to DC PV energy using Equation (1). The average system efficiency over the five-day observation period was 85.13%, which falls within the acceptable range reported in comparable residential off-grid PV studies. Zhao et al. (2020) reported system efficiencies between 80–90% for similar off-grid configurations under tropical conditions [11], suggesting that the present system performs competitively. The daily efficiency values ranged from approximately 80.1% on 11 June to 106.6% on 14 June. The value exceeding 100% on 14 June is physically explained by the discharge of previously stored battery energy to the load, rather than real-time PV generation — a normal operating behavior of battery-buffered off-grid systems that should not be interpreted as a measurement error. Additionally, the Performance Ratio (PR) of the system can be estimated as $PR = E_{AC}/(G_H \times A \times \eta_{STC})$, where the average daily AC output of 5.75 kWh, combined with an estimated peak sun hour of 4.5 h/day and the rated panel efficiency, yields a PR of approximately 0.80–0.85. This value is consistent with the internationally recognized benchmark of 0.70–0.85 for well-performing residential PV installations [12].

Figure 11 illustrates the comparison between PV energy production and AC energy consumption. The results confirm that the designed off-grid PV system can operate reliably and sustainably, supporting household electrical needs while integrating smart monitoring features.

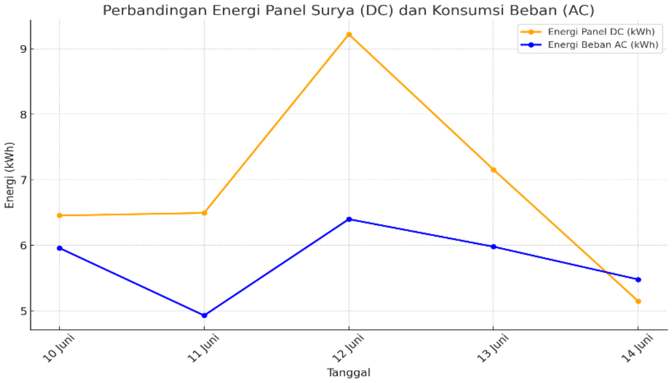

Figure 11. Comparison of Solar Energy Production and AC Energy Consumption

IV. Conclusion

Based on the research results and data analysis, the designed off-grid photovoltaic power system (PLTS) for smart home applications demonstrates efficient and stable performance. During five days of observation, the daily energy production ranged from 5.148 kWh to 9.222 kWh. On four of the observed days, the generated energy exceeded household electricity demand, while on one day the generated energy was slightly lower than the load requirement but was still adequately supplied through the battery storage system. This indicates that the system is capable of independently supplying household electrical needs.

Optimal power generation occurred between 10:00 and 14:00, with a peak current of 31.6 A and a maximum battery voltage of 54.4 V, confirming effective energy conversion and storage performance. Furthermore, the integration of a WiFi-based Smart MCB enables real-time energy monitoring, providing users with direct access to consumption data and system status. This monitoring capability supports the early implementation of an efficient and adaptive smart home energy management system.

Overall, the results confirm that the off-grid PLTS system is reliable and suitable for residential smart home applications, particularly in reducing dependence on conventional grid electricity. The system's average efficiency of 85.13% and an estimated Performance Ratio of 0.80–0.85 are consistent with benchmarks reported for well-performing residential PV installations in tropical climates [12], further validating the practical viability of this design.

This study has several limitations that should be acknowledged. The performance measurement was conducted over a five-day period, which, while capturing variation in daily irradiance conditions, may not fully represent seasonal or long-term behavioral trends of the system. The measurement duration is consistent with preliminary validation studies reported in recent literature [11], but extended monitoring over 30 days or more would yield statistically more robust performance indicators. Additionally, the current implementation focuses on monitoring and manual switching via the ATS; future work should explore deeper smart home integration, including automated load scheduling, predictive energy management, and demand-response algorithms. Incorporating weather-based forecasting and machine learning-driven optimization would further strengthen the system's classification as a fully smart home energy management solution.

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