Monitoring System Design for Off-Grid Solar Power Plant Based on Internet of Things

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ABSTRACT

Solar energy can be converted to electrical energy directly using photovoltaic (PV) modules. The output of electrical energy from the PV module is affected by the intensity of solar radiation and temperature. This study aims to monitor the output power of a solar power plant against changes in solar irradiation and temperature based on the Internet of Things (IoT). Off-grid solar power plants consist of PV modules, solar charge controllers, and batteries. The variables measured are output power, irradiation, module temperature, environment temperature, battery charge, discharge current, and system voltage. All measurement results are sent via the internet to the Thing Speak web server to be stored and displayed on a computer or android device connected to the internet. This monitoring system can monitor the real-time conditions of off-grid solar power plants. Monitoring results on 25 October 2022 showed the highest energy was 128 Watt hours with an efficiency of 16.06%.

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1. INTRODUCTION

Currently, more than 80% of the electricity demand in Indonesia comes from fossil energy sources such as oil, gas, and coal. The fossil energy prices increase because limited availability. In addition, fossil energy is not environmentally friendly. The need for electrical energy that continues to increase without being balanced with other alternative energy sources that can be converted into electrical energy is the cause of the electricity crisis. It is necessary to develop alternative energy as a source of electrical energy. Renewable energy sources are one of the alternative energies that can overcome the electrical energy crisis sourced from fossil energy. Renewable energy is an effort to offset the use of fossil fuel energy.

The solar power plant generates electrical energy from renewable energy sources, namely solar irradiation. Solar irradiation is converted into electrical energy directly using solar modules. The size of the output power generated by the solar module depends on how much light the solar module absorbs. Several factors, including solar irradiation, temperature, and wind speed, influence the performance of solar modules. Solar power plants need to be monitored in real-time to get optimal performance. Monitoring in real-time can provide information on the system's operating conditions and operating status **[1]–[6]**.

Internet development is speedy, both supported by a network infrastructure that continues to grow, which has a terrific impact on monitoring and control systems development. This internet development allows each device to have an identity that can be monitored and controlled remotely. This technology is called the Internet of Things (IoT). IoT in the monitoring system has been significantly developed, which has dramatically helped in remote monitoring at a low cost. IoT enables interaction between equipment connected to the internet and equipment-to-user communication. Application of IoT utilization in the system to facilitate monitoring and control as in **[7]–[9]**.

This study aims to design an Off-Grid Solar Power Plant Based on the Internet of Things to monitor real-time system performance. This article is structured in the first part as an introduction, followed by off-grid solar power generation and IoT-based monitoring system design procedures in sections 2 and 3. Section 4 is the results and discussion, and the final section is the conclusion.

2. OFF-GRID SOLAR POWER PLANT

Solar Power Plant is a power plant that uses sunlight through solar cells (photovoltaic) to convert solar photon radiation into electrical energy. Solar cells are thin layers of pure silicon (Si) semiconductor material, or other semiconductor materials, assembled into solar modules.

There are two types of solar power plants, namely on- and off-grid solar power plants. Off-grid solar power plants require batteries to store electrical energy, but not on-grid solar power plants. While the other constituent components are the same.

The solar module is the main equipment of the solar power generation system, which functions to convert solar light energy into electrical energy directly. The amount of output power generated from the conversion process is determined by several environmental conditions where a solar module is located, such as sunlight intensity, temperature, direction of sunlight, and sunlight spectrum. Environmental conditions that always change over time cause the output power of solar modules to also fluctuate **[7].**

The solar module's current and voltage characteristics (I-V) describe the energy conversion capability under certain conditions of solar radiation and temperature of the solar module. The I-V characteristics of solar modules can be maintained if the intensity of solar radiation and temperature is constant **[10].**

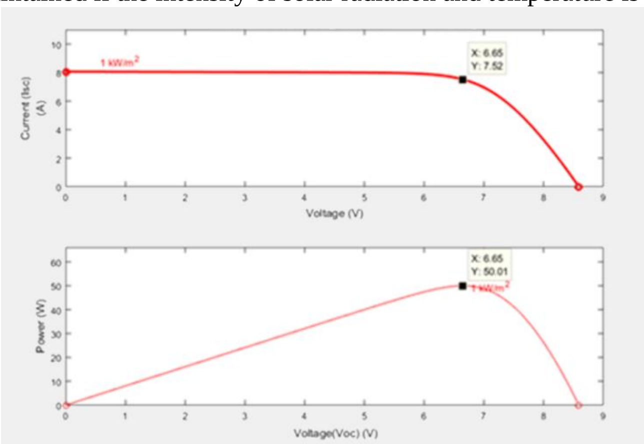


Fig. 1. I-V and P-V Relationship Curves

Fig. 1 is the characteristic curve of the solar module. The curve shows the relationship between voltage versus current and voltage versus power. The relevant equation for deriving the electrical parameters from the I-V curve and the P-V curve is in Equation 1.

$$P_{in} = I_{rr} \times A \quad (1)$$

where P_{in}, I_{rr}, and *A* are input power (Watt), irradiation (Watt/m2), and module area (m2), respectively.

An increase in solar irradiance on the module will cause an increase in V_{mp} as a function of the logarithm of the intensity ($V_{mp} = c \times \ln(P_{in}/P_{out})$ with *c* and P_{out} being constant factors). If the cell temperature does not change; in detail, it is not the irradiation power that has a linear relationship with the short-circuit current but the number of photons with energies higher than the proportional band gap.

$$P_{max} = V_{mp} \times I_{mp} \quad (2)$$

where P_{max}, V_{mp}, and I_{mp} are power at maximum power point (Watt), the voltage at maximum power point (Volt), and current at maximum power point (Amp.), respectively.

In addition to the main factors of solar radiation, ambient temperature is one of the factors that can affect the performance of solar modules. The temperature of the solar module has a linear function of the ambient temperature. *NOCT* measures the temperature reached by solar radiation under conditions of 800 W/m2 irradiation with a wind speed of 1 m/s and an ambient temperature of 20 ℃. The equation for predicting the surface temperature of the solar module is shown in equation 3.

$$T_{mod} = T_{amb} + G\left(\frac{NOCT-20}{800}\right) \quad (3)$$

where T_{mod}, T_{amb}, *G*, and *NOCT* are solar module temperature (℃), the ambient temperature around the solar module (℃), irradiation (W/m2), and Nominal Operating Cell Temperature (℃), respectively.

The solar module's efficiency is the ratio between the solar cell's maximum electrical power to the solar cell's output power. The efficiency equation can be written in Equation 4.

$$\eta = \frac{P_{max}}{P_{in}} \times 100\%$$

$$\eta = \frac{I_{mp} \times V_{mp}}{irradiation\ (S_T) \times solar\ module\ area (A)} \times 100\%$$

$$\eta = \frac{V_{oc} \times I_{SC} \times FF}{(S_T) \times A} \times 100\% \quad (4)$$

where V_{oc}, I_{sc}, and FF are open circuit voltage (Volts), short circuit current (Amp.), and Fill Factor, respectively.

The energy yield of a PV system represents the final energy output from the storage (battery) used by the DC load. The usability of this PV system is the final or final energy that the load will use for a particular time (t). The equation for energy is shown in Equation 5.

$$Ep = P_{out} \times t \quad (5)$$

Solar Charge Controller (SCC) is one of the components of an off-grid solar power generation system. SCC functions as a regulator of electric current for incoming current from the solar module and outgoing or used load current [11].

A battery or storage battery is a secondary cell or element and is a direct current source that can convert chemical energy into electrical energy. Batteries consist of wet batteries, hybrid batteries, calcium batteries, maintenance-free batteries, and sealed batteries. The battery also has a limit on the depth of discharge (discharge) contained in the battery. Depth of Discharge (DoD) is the depth limit of power expenditure, where the depth of discharge of DoD is 100%. Battery manufacturers always give a battery DoD rating of 80%, which means that only 80% of the available energy is released, and 20% remains in reserve [7].

3. MONITORING SYSTEM DESIGN PROCEDURE BASED ON IoT

The Internet of Things, also known by the acronym IoT, is a form of connection that is interconnected and capable of producing information that can be accessed and used by humans and other systems. Kevin Ashton first raised the initial idea of the Internet of things in 1999, where objects around us can communicate through a network such as an internet [8].

Things Speak is used for IoT analytics platform service. Things Speak is an open-source Internet of Things (IoT) application platform and API for storing and retrieving data from things using HTTP over the Internet or a Local Area Network. Thing Speak has integrated support from the numerical computing software MATLAB and Math Works. Allows Thing Speak users to analyze and visualize uploaded data using MATLAB without requiring the purchase of MATLAB and Math Works licenses [2].

The design stages start with identifying the problem, literature study, system requirements analysis, system design, testing, implementation, and analysis of design results. Problem identification involves designing the system and the required equipment (hardware and software) to complete the system design for IoT-based monitoring. Literature study refers to the tool's specifications to be designed and the theoretical basis needed to realize the tool's design. This literature study is to obtain information related to monitoring system research in the form of books, e-books, journals, and articles.

3.1. System Requirements

This study uses several tools and materials for design and data collection. Tables 1 and 2 are tools and materials used in research.

Table 1. Tools

No	Name	Remarks
1	Asus X441U laptop with Intel(R) Core 7020u processor, CPU @2.10 GHz 2.30GHz, 4.00 GB RAM, Windows 10, 64–bit operating system.	Laptop as a tool for making research reports and applying software such as Arduino IDE, Microsoft Word, and Microsoft Excel.
2	Arduino IDE	Arduino IDE is a software tool for sketching programs or programming media for Arduino.
3	Toolset	Toolset as an auxiliary tool for assembling a monitoring system.
4	Kyoritsu 1011 multimeter	As a tool for system testing.
5	Uni-T thermometer	Used for calibration of the module temperature sensor.
6	Digital thermometer	Used for calibrating the ambient temperature sensor.
7	Solar power meter SM206	Used for calibration of irradiance sensor.

3.2. System Design

System design is a stage that aims to make the system work properly. System design comprises several steps, including designing sensor circuits, RTC circuits, and ESP32 circuits with Arduino UNO. The block diagram of the IoT-based monitoring system design circuit is shown in **Fig. 2**.

Table 2. Materials

No	Name	Remarks
1	Arduino Uno R3	As the main controller, it receives measurement result information from sensors, receives time data from the time module, forwards this information to the LCD, and sends it to the cloud using Wi-Fi via ESP32.
2	Solar Module.	As a equipment for converting solar energy into electrical energy.
3	Sealed battery MF.	As equipment to store electrical energy and provide electrical energy to the load.
4	30 Watt DC lamp.	As a load.
5	ESP32 microcontroller.	As a connecting medium between Arduino Uno and the cloud via Wi-Fi, it supports IoT application systems.
6	PYR20 irradiance sensor.	The sensor is used to detect the intensity of sunlight.
7	MLX90614 temperature sensor.	As equipment to measure the temperature of solar modules and the environment.
8	Voltage Sensors.	Sensor to detect system voltage value.
9	ACS712 30A Current Sensor.	Sensors to detect the current flowing to/from the battery and to the load.
10	Real Time Clock (RTC).	A clock is a chip that can accurately calculate and store time data in real-time.
11	4×20 LCDs.	As a viewer of local monitoring data in real-time.
12	Power Supply 24 Volts.	Voltage supply for Arduino UNO, ESP32, and Sensors.
13	LM2596 step down DC- DC.	As equipment to reduce the voltage from the power supply to Arduino UNO and ESP32
14	Thing Speak servers.	As a monitoring data viewer media on Android through the Thing Show application and data recording.

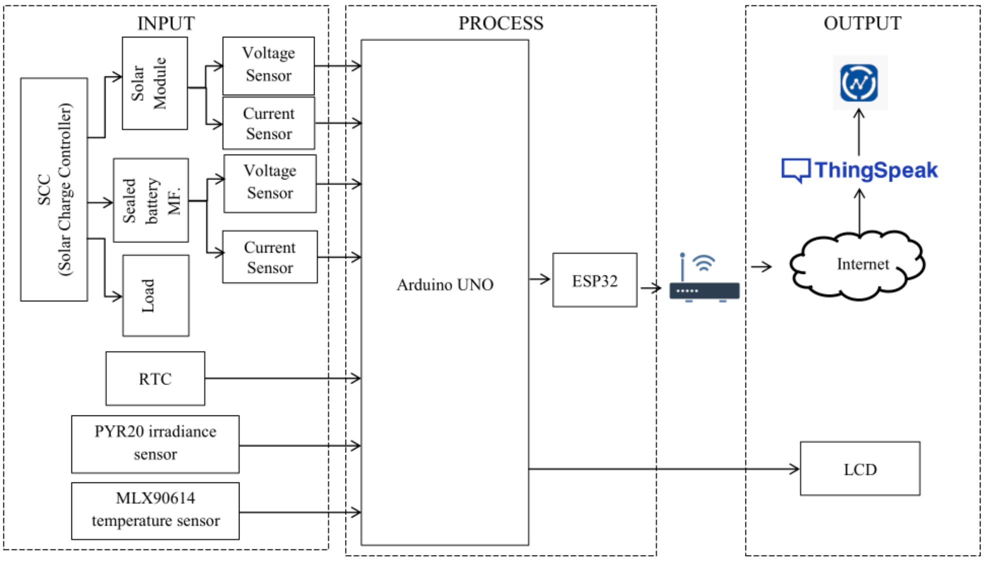


Fig. 2. IoT-based monitoring system block diagram

3.3. System Testing & Implementation

System testing is done to see if the system is running as expected. If an error occurs, hardware and software repair is done again. The testing stages are as follows: Connecting the system to a voltage source and checking system components such as Arduino UNO and ESP32. Check the display of measurement results of sensors on the LCD. Checking data received by ESP via serial port from Arduino UNO. Checking the ESP32 Wi-Fi connection to a local access point connected to the internet. Check measurement results on the Thing Speak cloud. Calibrate sensor measurements with a reference meter such as the Kyoritsu 1011 multimeter for current and voltage sensors. Digital thermometer and Uni-T thermometer for calibration of the MLX90614 temperature sensor, and solar power meter SM206 to calibrate the PYR20 irradiance sensor.

The linear equation of the calibration results based on the difference in measurements between the sensors and the reference measuring device is shown in Equation 6. Equation 6 uses a variable whose magnitude depends on the calibrated sensor output.

$$Y = a + bX \quad (6)$$

where Y, X, and a or b are measurement result variables, ADC input on the Arduino UNO is received from the sensor, and calibration results of constant, respectively.

The results of the calibration of the sensors using the approach of Equation 6 obtained: The measurement error of the PYR20 irradiation sensor against the reference measuring instrument Solar power meter SM206 is 1.79%, the measurement error of the voltage sensor is 0.4%, and the current sensor is 0.39% compared to the results of the multimeter measurement, the measurement error the MLX90614 temperature sensor for the module temperature is 0.42%, and the ambient temperature is 1.2% to the digital thermometer.

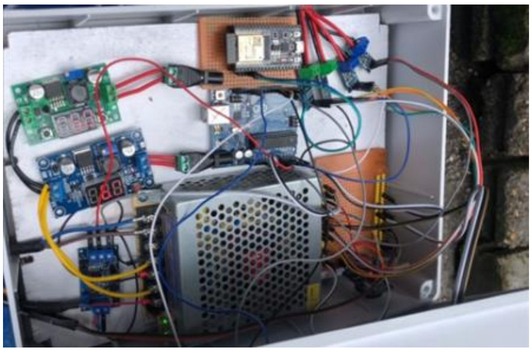
3.4. Analysis of Design Results

At this stage, an analysis of the results of monitoring the output of solar modules and battery conditions is carried out periodically. From these results, it can be concluded that the results of the design of an IoT-based monitoring system and the performance of an off-grid solar power generation system.

4. RESULTS AND DISCUSSION

The hardware realization of a solar power plant monitoring system based on the Internet of Things is shown in **Fig. 3**. The local monitoring system uses a panel box with an LCD to display measurement data locally. Fig. 3(a) and (b) are the panel boxes of the monitoring system front and inside view.

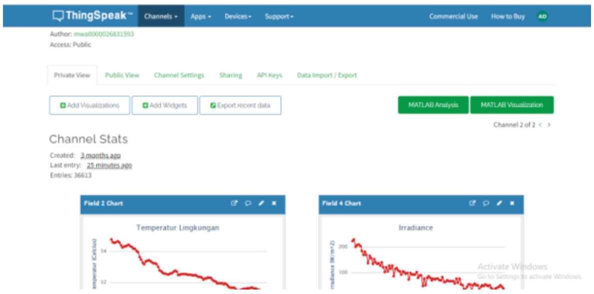
a. Front view



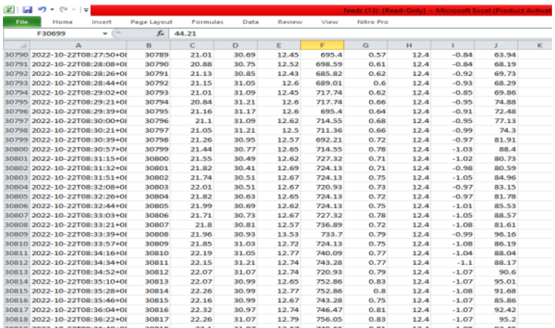
b. Inside view

Fig. 3. The results of the hardware design of the monitoring system

Sensor measurement results processed by Arduino UNO are sent to ESP32 via serial communication. All measurement results are sent serially and in real-time. The measurement data sent includes voltage, current, time, temperature, and irradiation. ESP32 forwards data to the Thing speak web server. Sending real-time data to the Thing speak web server. Thing Speak web server received that data is delayed 15 seconds. Data display on the web server can be seen in **Fig. 4.** Fig. 4(a) and (b) are graphical and numerical data displays on the web server. The data stored on the Thing speak web server is the same as displayed on the LCD.



a. Graphical display



b. Numerical dispaly

Fig. 4. Web server view

4.1. Monitoring System Test Results

The monitoring system test results include solar module temperature (T_{mod}), ambient temperature (T_{amb}), irradiance (I_{rr}), current from the solar module to SCC (I_{out}), solar module voltage (V_{out}), battery voltage (V_{batt}), current to/from a battery (I_{batt}), and the energy generated by the solar module. Data collection for off-grid solar power generation systems was carried out for seven days from 21 to 27 October 2022. In the time range from 07:00 – 21:00, data is stored every 30 minutes. The data collection process in the off-grid power generation system is shown in **Fig. 5**.

Fig. 5. Monitoring the operation of off-grid solar power plants

The measurement results on October 1, 2022, are shown in **Table 3**.

Table 3. Monitoring results of off-grid solar power generation systems

Time	T_{mod1} (°C)	T_{amb} (°C)	I_{rr} (W/m^2)	I_{out} (A)	V_{out} (V)	V_{batt} (V)	I_{batt} (A)	Energy (Wh)	Weather	Status
07:00	10.24	25.37	88.00	0.19	9.67	11.80	-0.01	0.91	Drizzle	Charge
07:30	11.74	26.95	94.30	0.23	9.77	11.92	-0.03	1.12	Drizzle	Charge
08:00	16.19	28.73	110.80	0.27	10.36	11.93	-0.06	1.39	Cloudy	Charge
08:30	31.10	34.09	714.55	0.95	12.60	12.30	-0.68	5.35	Sunny	Charge
09:00	36.82	34.05	880.54	1.30	13.16	12.45	-1.05	8.60	Sunny	Charge
09:30	39.54	35.67	1046.53	1.70	14.19	12.47	-1.40	12.10	Sunny	Charge
10:00	39.60	35.71	1052.09	1.89	14.43	12.47	-1.59	13.60	Sunny	Charge
10:30	39.01	36.35	1076.36	2.06	13.89	12.46	-1.76	14.30	Sunny	Charge
11:00	41.51	36.39	1077.12	2.18	14.06	12.50	-1.89	15.30	Sunny	Charge
11:30	42.54	36.41	1082.35	2.47	14.72	12.53	-2.08	18.20	Sunny	Charge
12:00	20.01	32.97	88.90	0.19	13.01	12.52	-0.04	2.30	Rain	Charge
12:30	34.55	34.65	538.98	1.18	13.50	12.52	-0.90	6.41	Sunny	Charge
13:00	28.76	34.01	210.20	0.42	13.11	12.55	-0.36	2.12	Drizzle	Charge
13:30	28.88	27.47	72.94	0.13	13.11	12.56	-0.12	0.59	Rain	Charge
14:00	28.48	25.33	36.20	0.05	13.06	12.40	0.00	0.00	Heavy rain	Discharge
14:30	28.60	25.13	37.83	0.08	6.16	12.56	-0.03	0.24	Cloudy	Charge
15:00	30.01	26.27	120.82	0.22	13.4	12.77	-0.18	1.14	Cloudy	Charge
15:30	34.34	28.07	194.24	0.37	13.31	12.78	-0.30	1.90	Cloudy	Charge
16:00	34.94	28.53	175.09	0.26	13.31	12.79	-0.26	1.34	Cloudy	Charge
16:30	34.19	29.41	108.05	0.11	13.31	12.79	-0.18	0.56	Cloudy	Charge
17:00	34.40	30.35	120.82	0.21	13.35	12.80	-0.30	1.08	Cloudy	Charge
17:30	33.13	29.03	15.48	0.03	3.84	12.94	-0.03	0.055	Cloudy	Charge
18:00	30.49	27.77	0.00	0.00	2.96	12.40	0.00	0.00	Night	Discharge
18:30	30.91	27.45	0.00	0.00	0.05	12.40	2.20	0.00	Night	Discharge
19:00	29.65	26.93	0.00	0.00	0.00	12.30	2.25	0.00	Night	Discharge
19:30	29.68	26.79	0.00	0.00	0.00	12.40	2.25	0.00	Night	Discharge
20:00	27.27	26.65	0.00	0.00	0.00	12.30	2.26	0.00	Night	Discharge
20:30	27.21	26.47	0.00	0.00	0.00	12.30	2.25	0.00	Night	Discharge
21:00	27.26	26.41	0.00	0.00	0.00	12.30	2.25	0.00	Night	Discharge

The results of solar module temperature measurements vary significantly with the ambient temperature. Table 3 shows that the temperature of the solar module can be higher or lower than the ambient temperature. The weather causes this difference. In cloudy and rainy weather, the temperature of the solar module is lower than the ambient temperature. In comparison, during hot weather and at night, the module temperature is higher than the ambient temperature. Solar modules receive and release heat faster because the density of the module is higher than that of the environment. The battery current (I_{batt}) has a charge and discharge status. Discharge status means that I_{batt} supplies current to the load, while charge means that the solar module provides current to the battery. Weather greatly influences the current generated by solar panels. Table 3 shows that the output current of solar modules varies. The temperature of the solar module is very variable. It tends to be more influenced by weather than irradiation. As a comparison, the calculation of the temperature of the solar module due to irradiation is carried out.

Output power, module temperature, and system efficiency can be calculated using Equations 2, 3, and 4. As an example of calculations using data at 11:30 from Table 3, the output power of the solar module can be obtained as follows:

$$P_{out} = V_{out}\ x\ I_{out}$$
$$= 14.72\ x\ 2.47$$
$$= 36.36\ Watt.$$

The input power of the solar module is as follows:

$$P_{in} = I_{rr}\ x\ A$$
$$= 1082.2\ x\ 0.3618$$
$$= 391.53\ \text{Watt.}$$

Table 4. Output power, module temperature, and efficiency

Time	T_{amb} (°C)	T_{mod1} (°C)	T_{mod2} (°C)	I_{rr} (W/m^2)	I_{out} (A)	V_{out} (V)	P_{out} (Watt)	Energy (Wh)	Weather	Efisiensi (%)
07:00	25.37	10.24	28.12	88.00	0.19	9.67	1.83	0.91	Drizzle	5.75
07:30	26.95	11.74	29.90	94.30	0.23	9.77	2.24	1.12	Drizzle	6.57
08:00	28.73	16.19	32.19	110.80	0.27	10.36	2.79	1.39	Cloudy	6.96
08:30	34.09	31.1	46.42	714.55	0.95	12.6	10.71	5.35	Sunny	4.14
09:00	34.05	36.82	51.57	880.54	1.3	13.16	17.11	8.60	Sunny	5.37
09:30	35.67	39.54	58.37	1046.53	1.7	14.19	24.12	12.10	Sunny	6.37
10:00	35.71	39.6	58.59	1052.09	1.89	14.43	27.27	13.60	Sunny	7.16
10:30	36.35	39.01	59.99	1076.36	2.06	13.89	28.61	14.30	Sunny	7.34
11:00	36.39	41.51	60.05	1077.12	2.18	14.06	30.65	15.30	Sunny	7.86
11:30	36.41	42.54	60.23	1082.35	2.47	14.72	36.36	18.20	Sunny	9.21
12:00	32.97	20.01	35.75	88.90	0.19	13.01	1.95	2.30	Rain	6.06
12:30	34.65	34.55	41.49	538.98	1.18	13.5	12.83	6.41	Sunny	6.58
13:00	34.01	28.76	30.58	210.20	0.42	13.11	4.24	2.12	Drizzle	5.58
13:30	27.47	28.88	29.75	72.94	0.13	13.11	1.18	0.59	Rain	4.47
14:00	25.33	28.48	25.33	36.20	0.05	13.06	0.00	0.00	Heavy rain	0.00
14:30	25.13	28.6	26.31	37.83	0.08	6.16	0.49	0.24	Cloudy	3.58
15:00	26.27	30.01	30.05	120.82	0.22	13.4	2.28	1.14	Cloudy	5.22
15:30	28.07	34.34	34.14	194.24	0.37	13.31	3.81	1.90	Cloudy	5.42
16:00	28.53	34.94	34.00	175.09	0.26	13.31	2.68	1.34	Cloudy	4.23
16:30	29.41	34.19	32.79	108.05	0.11	13.31	1.13	0.56	Cloudy	2.89
17:00	30.35	34.4	34.13	120.82	0.21	13.35	2.17	1.08	Cloudy	4.96
17:30	29.03	33.13	29.51	15.48	0.03	3.84	0.11	0.055	Cloudy	1.96
18:00	27.77	30.49	27.77	0.00	0.00	2.96	0.00	0.00	Night	0.00
18:30	27.45	30.91	27.45	0.00	0.00	0.05	0.00	0.00	Night	0.00
19:00	26.93	29.65	26.93	0.00	0.00	0.00	0.00	0.00	Night	0.00
19:30	26.79	29.68	26.79	0.00	0.00	0.00	0.00	0.00	Night	0.00
20:00	26.65	27.27	26.65	0.00	0.00	0.00	0.00	0.00	Night	0.00
20:30	26.47	27.21	26.47	0.00	0.00	0.00	0.00	0.00	Night	0.00
21:00	26.41	27.26	26.41	0.00	0.00	0.00	0.00	0.00	Night	0.00

The temperature of the solar module can be known from the ambient temperature using Equation 3, as follows:

$$T_{mod2} = T_{amb} + G\left(\frac{NOCT-20}{800}\right)$$

$$T_{mod2} = 36.41 + 1082.2\left(\frac{45-20}{800}\right)$$
$$T_{mod2} = 60.23\ ^{o}\text{C}.$$

Solar module efficiency can be calculated using equation 4, as follows:

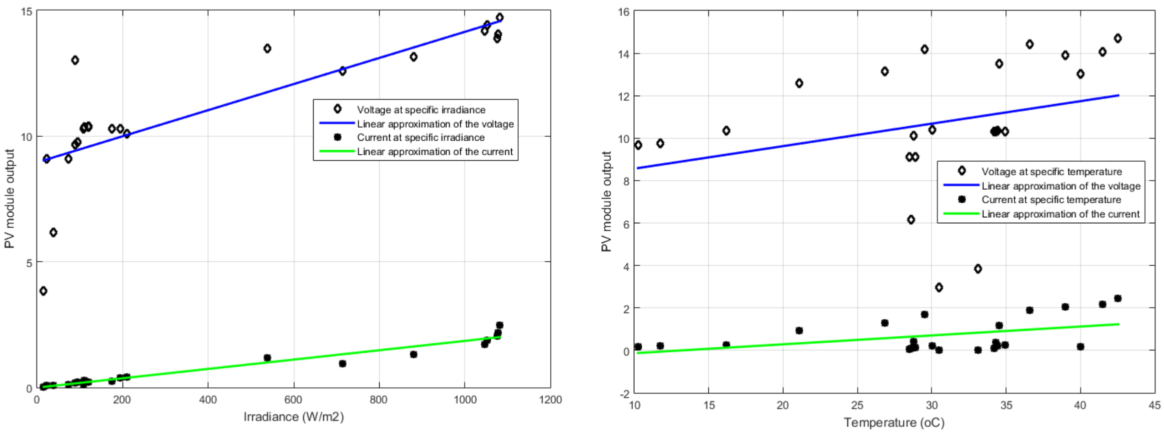
$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\eta = \frac{36.36}{391.53} x100\% = 9.21\%$$

In the same way, using equations 2 to 4, the output power, module temperature, and panel efficiency for every half hour (data in Table 3) are shown in Table 4.

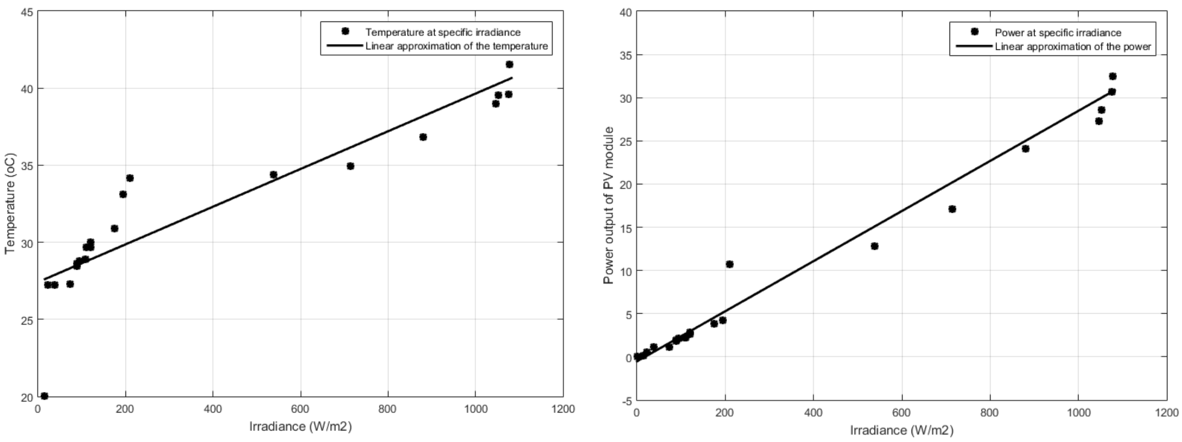
Table 4 shows that T_{mod1} is different from T_{mod2}. T_{mod1} is the module temperature resulting from sensor measurements, and T_{mod2} is the module temperature resulting from Equation 3. T_{mod1} is more valid than T_{mod2} because the Equation to obtain T_{mod2} depends on irradiation and ambient temperature without considering the weather, so the temperature value of T_{mod2} is higher than T_{mod1}. The highest power output and module efficiency at 11:30 am. Because at that time, the radiation was highest, and the weather was sunny. The output power at 11:30 am with an irradiance of 1082.35 Watts/m2 is 36.36 watts. The energy generated by the solar module for charging the battery is 108.66 Watt hours, with the most excellent efficiency of 9.21%.

4.2. Analysis of Off-Grid Solar Power Plant Monitoring Results



a. Irradiance to output voltage and current b. Temperature to output voltage and current

Fig. 6. Effect of irradiation and temperature on the output voltage and current of the solar module



a. Temperature change due to irradiation b. Output power change due to irradiation

Fig. 7. Effect of irradiation on temperature and output power of solar module

Comparative analysis of irradiance, temperature, voltage, current, and energy based on the monitoring results of an IoT-based solar power generation system can be seen in **Fig. 6** to **Fig. 8**. Fig. 6(a) shows the effect of irradiation on the output voltage and current of the solar module. Using a linear approach, an increase in irradiation causes an increase in the output voltage and current of the solar module. Fig. 6(b) shows the relationship between temperature to the output voltage and current. Using a linear approach, an increase in temperature increases the output voltage and current of the solar module. The increase in the output voltage and current due to the temperature rise is lower than the increase in the output voltage and current due to irradiation.

Fig. 7(a) is a graph of the relationship between changes in irradiation and temperature. Increasing irradiation causes the temperature to increase linearly. Fig. 7(b) shows the relationship between irradiation changes and the solar module's output power. The increase in irradiation causes the power output of the solar module to increase linearly.

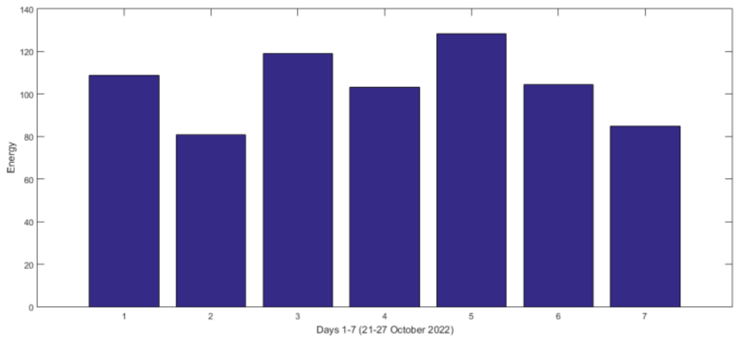


Fig. 8. Total energy per day from 21-27 October 2022

Fig. 8 shows the total daily energy generated by solar modules from 21-27 October 2022. The energy produced per day varies due to unpredictable weather. The weather was sunny, but suddenly it rained very heavily, so the power output of the solar module was zero. That week's highest daily energy was on October 25, 2022, at 128.4 Wh. Meanwhile, the lowest daily energy was 80.8 Wh on October 22, 2022.

5. CONCLUSION

The Internet of Things (IoT)-based off-grid solar power plant monitoring system manages to monitor the input/output of solar modules and battery conditions in real-time via the LCD and access to the Thing Speak web server or Android. Monitoring was carried out for a week. The highest output voltage and current were 15.30 V and 2.38 A at a module temperature of 48.05^o C and an ambient temperature of 36.95^o C. The highest voltage and battery charge currents are 14.3 V and -2.3 A, with a power of 36.36 Watts at an irradiance of 1096.81 W/m^2. The highest energy per day was 128.4 Wh on October 25, 2022, with the highest efficiency of 16.06%.

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