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Monitoring and Evaluation Electrical Power Control in Solar Power Systems Based on IoT

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Abstract

This study aims to develop a monitoring and electrical power control system for solar power systems based on IoT. The problem addressed is how to monitor and control the electrical power usage from solar panels in real-time over the internet, as well as how to limit the electrical power used by AC loads for energy efficiency. The system is equipped with sensors to measure current, voltage, and light intensity, controlled by an ESP32 microcontroller. Sensor data is processed and displayed in the form of graphs on a web page in real-time. The system also includes additional controls to connect and disconnect the electric current to AC loads, and limit the electrical power, allowing users to manage electrical energy usage efficiently. The research methodology includes several stages: designing the system block diagram, developing the hardware and software, implementing and integrating sensors with the ESP32 microcontroller, and testing the entire system. The results show that the prototype system can function according to the initial design. The system can record current, voltage, power, and light intensity in real-time and display them as graphs and tables on the website. AC load control and power limiting on AC loads can operate according to user commands. Measurements from a 10 Wp solar panel show maximum intensity around noon under sunny conditions, producing a current of up to 0.45 Ampere. The efficiency of the solar panel in this prototype is 12.16%, indicating a need for improvement for more effective use. The main contribution of this research is the development of an integrated monitoring system with web-based electrical power control, enabling users to monitor and manage solar power systems efficiently and in real-time

Keywords *— Battery, ESP32, Real Time, Solar Cel l, Website*

1. INTRODUCTION

The introduction outlines the background of the problem being solved, the issues related to the problem being solved, the research reviews that have been done before by other researchers that are relevant to the research conducted The development of sensors and IoT (Internet of Things)[1] technology can be used as the main component of a photovoltaic[2] system to monitor promptly[3-5], collect In the current condition of the COVID-19 pandemic, electricity is the main component to meet the daily needs of humans, especially those who work and study from home. Almost all equipment used to facilitate human work requires electrical energy, such as lamps, household appliances, equipment in the world of health, production equipment, and others, most of which require electrical energy[6]. Most of the electrical energy needs in Indonesia still come from non-renewable natural resources such as fossil fuels[7]. Indonesia is a tropical country traversed by the equator so that it gets sunlight all year round. With Indonesia's geographical conditions that can utilize solar energy as a potential and environmentally friendly alternative source of electrical energy[8].

To generate electricity from solar energy, a semiconductor component is needed, namely solar cells. The utilization of solar energy by applying solar cells as a producer of electrical energy is called Photovoltaic (PV) technology[9-10]. The electrical energy produced depends on several factors such as the material of manufacture, the intensity of sunlight, the temperature[11], and the position of the solar cell[12] concerning the direction of the sun's rays[13-15]. Generally, the cross-section of the solar cell module is mounted facing one particular direction[16]. The daily apparent motion of the sun causes the sun to change its position every day so that the solar cell does not always get the maximum light intensity so that the resulting voltage is less than optimal[17-20].

The development of sensors and IoT (Internet of Things) technology can be used as the main component of a photovoltaic system to monitor promptly, collected, and sent to a cloud server via wired or wireless communication for analysis[21]. Photovoltaic power system[22] data collected by sensors is more complex than usual[23], which presents a lot of uncertainty in terms of volatility, variability, and randomness due to the chaotic nature of the weather system[24]. The application of these sensors is used as a reference to allow for voltage losses that occur so that there are different results[25]. The main contributions of the paper are:

- Make the architecture of the solar power system monitoring system further.
- The electrical power each device can be limited through the website that has been developed.
- Presenting data analysis on the monitoring website making easier to read the results of each sensor processed through the microcontroller.

Therefore, it is necessary to monitor the use of batteries in this solar power plant[26], so that the use of current, voltage, and solar panel battery power can be monitored continuously. There is a minimum and maximum capacity of electrical energy stored in the battery[27-28] in the form of battery status (full/empty) which can later be used as a source of electrical energy in power units[29]. There are additional connecting and circuit breaker controls to AC loads, as well as an electric power limiter so that users can regulate the use of electrical energy in AC loads. Parameters of current, voltage, power, and sunlight intensity received on solar panels can be monitored continuously via the internet remotely via the web anytime and anywhere.

2. RESEARCH METHOD

2.1. System Block Diagram

System planning in the form of block diagrams is required before making a system that includes hardware and software. The following is a system block diagram image of the prototype Solar Panel Battery Monitoring System Tool Using a Web-Based ESP32:.

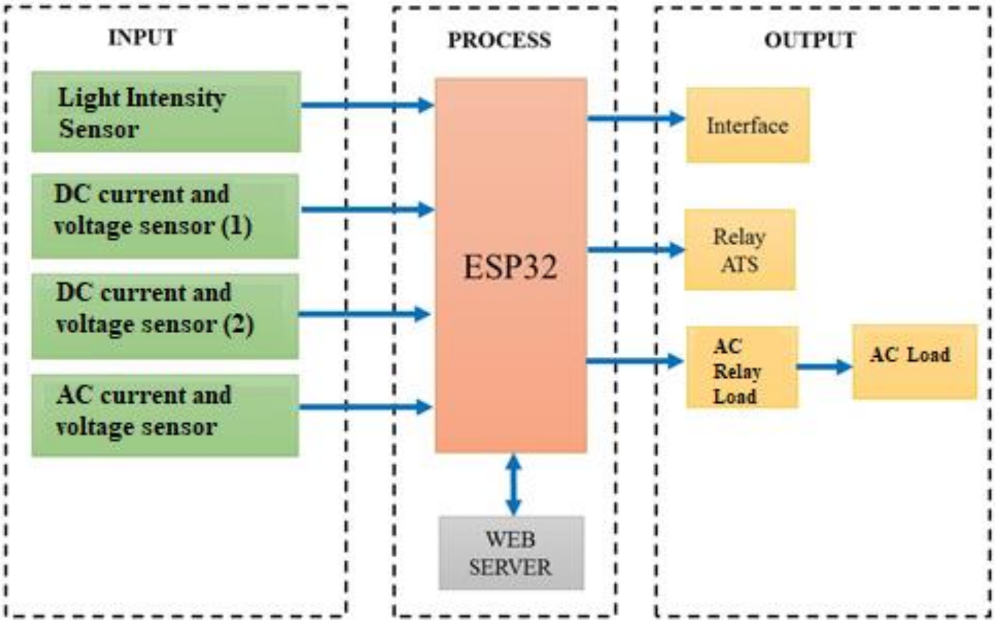

Figure 1. System block diagram

Block diagram of the system there is three parts, namely input, process, and output. In the input section, there is 1 BH1750 sensor to measure the intensity of sunlight received by solar panels, 2 INA219 sensors to measure DC voltage and current from solar panels and batteries, and 1 PZEM-004T sensor to measure AC and voltage from the inverter to load. The measurement results of the 4 sensors will be forwarded to the ESP for processing. In the process section, all sensors are controlled by the ESP32 which functions as a microcontroller equipped with a Wifi module that receives measurement data from the sensors. In this section, the ESP32 and the web server communicate with each other to receive and provide information. In the output section, the data that has been received by ESP32 will be displayed to the user via a web interface.

In this section there is an ATS relay that functions to control the on / off of the inverter, if the battery is empty then the inverter is off, if the battery is full, the inverter will be on. There is also an AC load relay that functions to control the AC load through 3 existing relays to cut or connect the electric current to the load and limit the value of the power entering the load.

The working principle of the tool in this design system starts from charging the battery using a solar panel with an SCC controller. In designing this monitoring system tool uses 2 INA219 sensors where one sensor is for current and voltage from the solar panel and the other sensor is for the current and voltage from the battery. There is 1 BH1750 sensor to measure the intensity of sunlight. The parameter values of the AC load are also monitored on the website with the help of the AC Voltage Current sensor, namely the PZEM-004T sensor. Through the web, the user can see a graph of the sensor readings, battery status, and give commands to turn on the AC load relay, if the relay is on then the load will be off so that it cannot be used, if the relay is off then the load will be on so it can be used. As well as setting the AC load output power limit, if it exceeds the power limit, the relay will turn off, if it does not exceed the power limit, the relay will stay on.

2.2. Electrical Design

The design used is an Offgrid Solar Home System (SHS) with an inverter so that this device can use AC loads. There are three types of Solar Panel Systems, namely Offgrid, Ongrid and Hybrid. The selection of the Offgrid type Solar Panel System because this type of Solar Panel System is most suitable for a system that is well made from a monitoring system. There are 3 types of sensors used to determine the condition of the Solar Panel System, namely INA219 which functions as a measure of the output value of the battery, both voltage value and current value because the INA219 sensor is a sensor that is devoted to measuring voltage and current from DC electricity, BH1750 which functions as measuring the intensity of sunlight received by the solar panel and the PZEM-004T Sensor to measure the current at AC Load. The design of the Solar Panel System is shown in Figure 2.

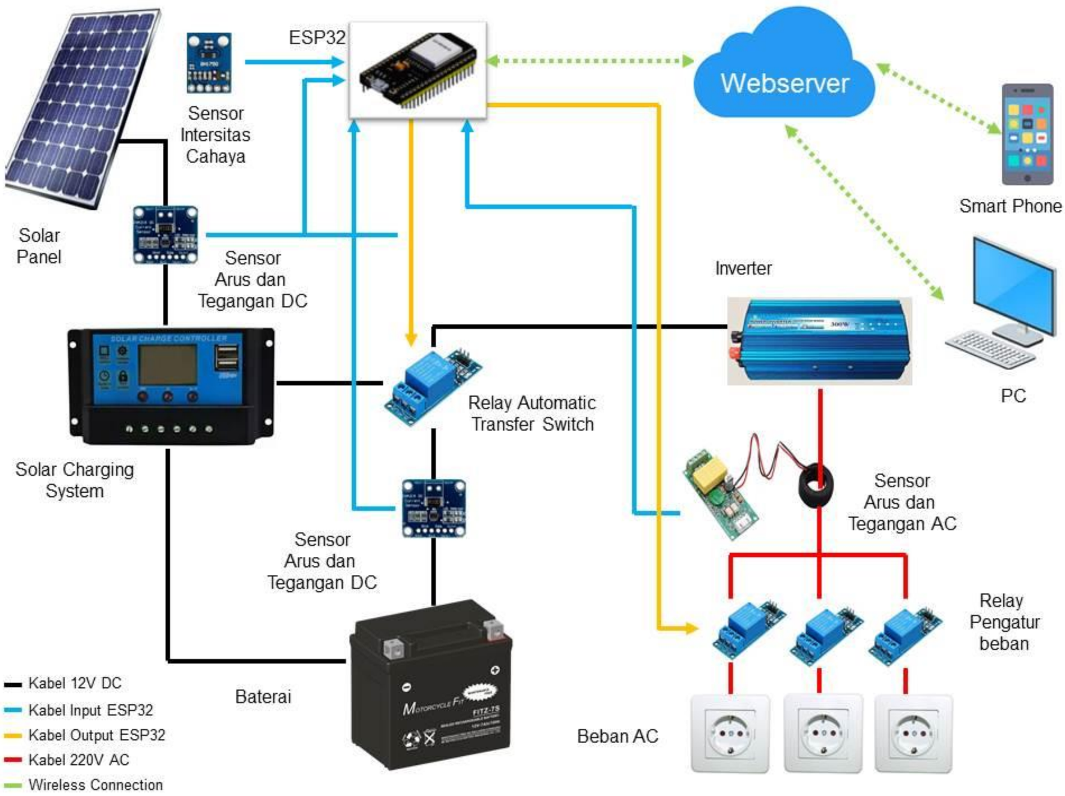

Figure 2. Solar Panel System Circuit Design

Based on figure 2, the first, solar panels capture solar energy by solar panels which are then converted into electricity with DC voltage and current. The panel used in this study is 10 WP which if calculated in a day can produce 35 Watts with the assumption of heating for 3.5 hours a day. On the solar panel, a light intensity sensor BH1750 is installed which functions to determine the intensity of sunlight received by the solar panel. Then forwarded to the Solar Charger Controller (SCC), the SCC function here is to set the voltage value to remain constant because the voltage value generated by the solar panel is unstable. The unstable voltage value will be stabilized by the SCC, which will then charge the battery.

The function of the battery in this system circuit is to store electricity and will be used when the solar panel cannot function properly, such as at night and covered by cloudy clouds where there is no sunlight. In this study, the battery used is the G Power 12V 9 Ah brand which, when calculated, can store and produce 108 Watts/hour with a full charge. Battery life depends on the load used, the greater the power consumption used, the faster the battery capacity runs out. In conditions of charging until fully charged, the battery can accommodate a voltage of up to ±12 Volts.

There is an INA219 sensor that functions to collect DC voltage and current data that will enter the SCC. From the SSC, solar energy is passed to the battery for storage. At night, the ATS (Automatic Transfer Switch) relay will connect the battery to the inverter so that the battery power can be used by the load. There is an INA219 sensor that is connected between the relay and the battery which functions to collect voltage and current data that will enter the battery. Electrical energy from the battery (12V DC voltage) will be forwarded to the inverter for later conversion to 220V AC voltage. After being converted to 220V AC voltage, it is forwarded to the load that has been connected to a relay that functions as a liaison/breaker in each load. There is a PZEM-004T sensor for data retrieval of AC that will enter the load.

BH1750 light intensity sensor, INA219 sensor and PZEM-004T sensor as ESP32 inputs. While the output of the ESP32 are relays connected to the load. From the system that has been designed, Esp32 functions as a microcontroller equipped with a Wifi module that will receive data, after the data from the sensors is obtained, the data is sent to the webserver to be read and stored in the database, then after being saved it will be directly stored. displayed on a web page so that it can be accessed by users via a web browser using a PC or smartphone

3. RESEARCH RESULTS AND DISCUSSION

3.1. Implementation

The panel box used to make this prototype tool is indoor with a size of 30 x 40 x 20 cm. For the ESP32, sensors (except light intensity sensors), inverters, and relays are placed in a panel box. The battery is placed outside the panel box. For the solar charger controller and 3 socket holes affixed to the door of the panel box. The hardware implementation in this research is by assembling electronic components that have been designed beforehand. The below is a hardware prototype for this final project which has been assembled in the image below:

Figure 3. Prototype design result

Following are the results of the software implementation in the form of a web-based on web-based software design that has been made. Below is a web menu display image which is a battery menu display that contains information on the status of the battery capacity (full/empty), if it is fully charged (± 12 volts) then the battery status changes to a full battery, if the battery capacity is empty (± 11 Volt) then the battery status changes to empty, battery voltage, battery current, battery power, limiting power which can be adjusted according to the user's wishes, 3 settings to adjust the AC load, namely on / off and the ATS battery relay to regulate the electric current flowing to the inverter. There is an export to excel button to download the measurement data for voltage, current, battery power, and a clock that shows the reading time.

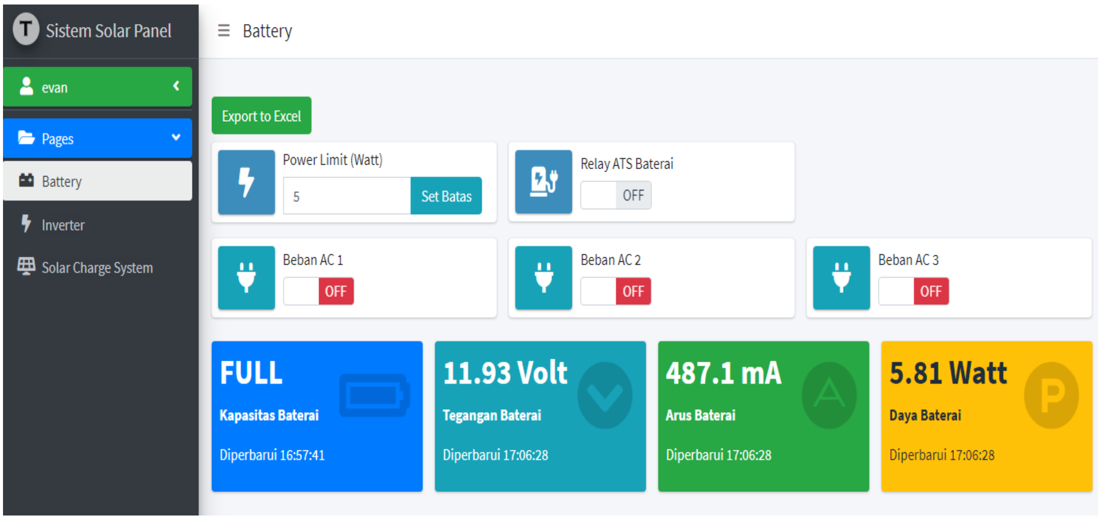

Figure 4. Display the battery menu on the web

Inverter menu display that contains information on AC and voltage coming from the inverter, displayed in the form of a line graph which is updated continuously and in real time. There is an export to excel button to download the measurement data for voltage, current, AC power, and a clock that shows the reading time.

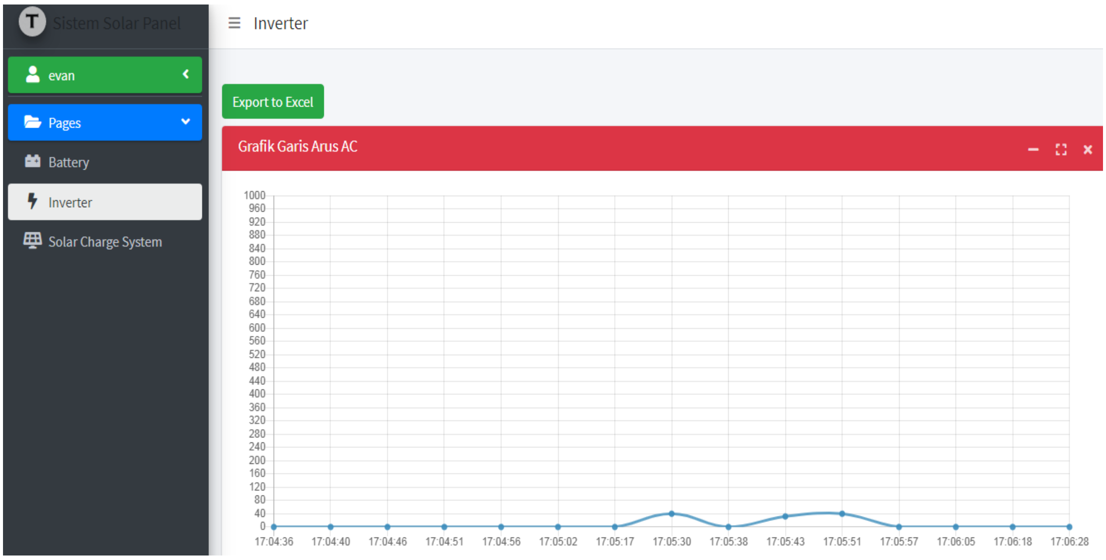

Figure 5. Display the inverter menu on the web

The solar charger system menu display contains information on the current and DC voltage coming from the solar panel to the SCC, the power generated from the solar panel, and the intensity of sunlight displayed in the form of a line graph which is updated continuously and in realtime. There is an export to excel button to download measurement data for voltage, current, DC power, light intensity, and a clock that shows the reading time.

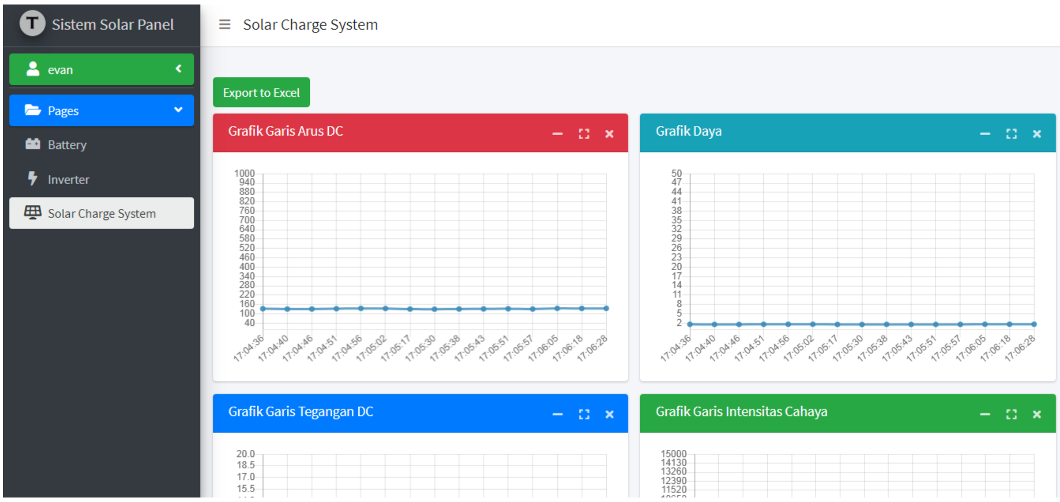

Figure 6. Display the solar charge system menu on the web

3.2. Testing solar cell 10 Wp

The solar panel The solar panel in this prototype is designed to convert sunlight into electrical energy. To evaluate its performance, a test was conducted by exposing the solar cells to sunlight under clear weather conditions during the day. The test aimed to measure the voltage, current, and power generated by the solar panel. Importantly, during this test, the battery was not connected to the solar panel, ensuring that the measurements reflected the panel's raw output without any influence from the charging process. Sampling data was collected over a period of approximately 15 minutes. The data was transmitted to the web interface, with the time of data reception dependent on the internet connection. The results are summarized in Table 1 below:

Table 1. The result solar cell 10 Wp

Minute-	Time (WIB)	Light Intensity (lux)	Voltage (V)	Current (mA)	Power (watt)
1	14:01:58	54612	19.61	40	0.78
2	14:02:53	54612	19.58	41.9	0.82
3	14:03:59	54612	19.58	41.9	0.82
4	14:04:49	54612	19.62	42.2	0.83
5	14:05:57	54612	19.6	41.9	0.82
6	14:06:59	54612	19.56	41.9	0.82
7	14:07:57	54612	19.53	41.7	0.81
8	14:08:59	54612	19.5	41.6	0.81
9	14:09:58	54612	19.44	41.5	0.81
10	14:10:59	54612	19.43	41.7	0.81
11	14:11:57	54612	19.41	41.9	0.81
12	14:12:59	54612	19.44	41.9	0.81
13	14:13:57	54612	19.38	41.5	0.8
14	14:15:03	54612	19.29	41	0.79
15	14:16:04	54612	19.25	41.1	0.79
The total power that goes into the solar panels					12.13
Average power per minute					0.80

Total Power Generated: 12.13 W, Average Power per Minute: 0.80 W. The solar panel used in this prototype is a Polycrystalline or polysilicon type. Based on the testing phase, this type of solar panel demonstrated consistent performance under stable sunlight conditions. Voltage Production: The voltage output ranged between 19.25 V and 19.61 V. This narrow range indicates that the panel was able to maintain a stable voltage output when exposed to consistent sunlight intensity. Current Generation: The maximum current measured was 41.9 mA. Current readings remained relatively stable throughout the test period, with minor fluctuations. The data indicates that the solar panel's performance is consistent under clear weather conditions. The voltage and current readings remained within expected ranges, and the power output was steady. These results are crucial for understanding the efficiency and reliability of the solar panel in converting sunlight into electrical energy. The consistent light intensity of 54,612 lux throughout the test period contributed to stable performance metrics. The average power output of 0.80 W per minute and the total power generated of 12.13 W demonstrate the capability of the solar panel to produce electrical energy efficiently under optimal conditions. However, further improvements in the system design and components may be necessary to enhance overall efficiency, especially under varying environmental conditions.

3.3. Testing INA219 sensor on the battery 12 V

The INA219 sensor testing was conducted to measure the voltage, current, and power on a 12V solar panel battery while it was charging and not connected to the inverter. The objective was to evaluate the sensor's accuracy and the battery's performance under these conditions. Sampling data was taken over a 15-minute period during late afternoon sunny weather. The time for receiving measurement data to the web depended on the internet network connection. The results are summarized in Table 2 below:

Table 2. The result INA219 sensor on the battery 12 V

Minute-	Time (WIB)	Light Intensity (lux)	Voltage (V)	Current (mA)	Power (watt)
1	14:52:49	16087	12.44	108.1	1.35
2	14:53:44	16023	12.48	108	1.35
3	14:54:48	15791	12.5	106.4	1.33
4	14:55:49	15658	12.51	106	1.33
5	14:56:46	15648	12.52	106.2	1.33
6	14:57:49	15456	12.17	104.8	1.28
7	14:58:49	15468	12.08	104.1	1.26
8	14:59:45	15342	12.06	101.4	1.22
9	15:00:48	15352	12.04	103.2	1.24
10	15:01:51	15235	12.1	102	1.23
11	15:02:51	15700	12.1	104.6	1.27
12	15:03:51	16105	12.04	105	1.26
13	15:04:52	15302	12.09	100.4	1.21
14	15:05:53	14652	12.08	97	1.17
15	15:06:59	15118	12.08	101.2	1.22
The total power that goes into the solar panels					19.05
Average power per minute					1.27

The INA219 sensor testing demonstrated its capability to accurately measure voltage, current, and power in real-time. Here are key observations from the test: Stable Voltage Output:The voltage readings consistently ranged between 12.04 V and 12.52 V, indicating stable performance of the battery under charging conditions. Current Fluctuations: The current measurements exhibited a slight decrease over the test period, starting at 108.1 mA and gradually decreasing to 97 mA. This indicates a gradual stabilization of the charging process as the battery approaches its full capacity. Consistent Power Output: The power output remained within a narrow range, averaging 1.27 W per minute. The total power accumulated was 19.05 W over the 15-minute period. The INA219 sensor proved to be an effective tool for monitoring the charging process of the solar panel battery. The test results showed that the sensor could accurately measure the voltage, current, and power, providing reliable data for real-time monitoring and analysis. The stable voltage and consistent power output highlight the efficiency of the solar panel system, even under late afternoon sunlight conditions. These results are crucial for optimizing the performance and efficiency of solar power systems in real-world applications.

3.4. Testing PZEM-004T sensor from the inverter to the AC load

Testing and analysis of the PZEM-004T sensor are carried out by taking the measured value of the voltage and current from the inverter to the AC load, when the ATS battery relay is ON, each AC load has been installed with 3 lamps with different power. AC load 1 has been installed with a lamp with a power of 7 Watt, AC load 2 has been installed with a lamp with a power of 3 Watt and AC load 3 has been installed with a lamp with a power of 1 Watt. The following is the test table for the measurement of the PZEM-004T sensor against AC load

Table 3. The result PZEM-004T sensor from the inverter to the AC load

Condition	Voltage (V)	Current (mA)	Power (watt)	Time (WIB)
AC load is not used	230.4	0	0	17:40:58
AC load 1 is used	231.6	54	6.5	19:00:00
AC load 1 and 2 is used	230.8	99	7.5	19:02:59
AC load 1,2 and 3 is used	227.4	101	8.5	19:04:14

Based on the PZEM-004T sensor testing phase, when the AC load is not used, the voltage measurement is 230.4 Volts AC with a current of 0 mA and a power of 0 Watt. When AC 1 load is used, the current increases to 54 mA and the power becomes 6.5 Watt. When AC loads 1 and 2 are used, the current increases to 99 mA and the power becomes 7.5 Watt. When AC loads 1, 2 and 3 are used, the current increases to 101 mA and the power becomes 8.5 Watt.

3.5. Testing Light Intensity Sensor (BH1750)

A test of the light intensity sensor (BH1750) was carried out to determine the measurement results of the light intensity sensor on battery charging within a certain time. This test is carried out by placing solar cells under exposure to sunlight in sunny weather conditions for ± 3 hours, the time of receiving measurement data to the web depends on the internet network connection so that the measurement results are obtained in the table below:

Table 4. The result Light Intensity Sensor (BH1750)

Time (WIB)	Light Intensity (lux)	Voltage (V)	Current (mA)	Power (watt)
11:56:35	32236	12.39	204.7	2.54
12:01:58	35025	12.34	236.5	2.92
12:04:18	54612	12.58	382.7	4.81
13:30:05	54612	12.83	456.3	5.86
13:45:34	54612	12.59	399.1	5.02
14:32:55	51191	12.38	118.2	1.46
14:33:13	43166	12.33	118	1.45
14:34:50	24107	12.31	118	1.45
14:35:55	22824	12.30	118	1.45
14:36:44	19015	12.51	117.6	1.47
15:01:01	15337	12.07	103.3	1.25
15:23:19	13389	12.49	92.6	1.16

Starting with the prototype of this tool it is turned on at 11:56:35 WIB in clear weather conditions, the results of the measurement of the light intensity sensor are 32,236 lux, which continues to increase until the light intensity is 54,612 lux at 12:04:18 WIB. The intensity of light began to decline at 14:33:13 WIB of 43,166 lux, continued to decrease until the light intensity was 13,389 lux at 15:23:19. We can conclude that the sun's light intensity peaks at 12:04 WIB in bright conditions and the sun feels stinging. In about 2 hours 30 minutes, the sunlight intensity is still stable at 54,612 lux. The intensity of sunlight has decreased in intensity, in sunny conditions but it is already evening at 14:35:55 WIB, sunlight has started to decrease and does not feel stinging.

3.6. Testing Relay module and Power Limiter

Indicates the relay can work properly with the AC Load output turning ON or ON. When the relay is not active, the AC load output turns off or turns off. The following is an example image of an AC load relay simulation when the AC load relay 1 is ON, the light will automatically turn on:

Figure 7. Testing Relay module

Knowing the power limit on the system software can work when the user enters the desired power limit value according to the battery power measurement results. The light will turn off when the power limit is less than the lamp power used in the AC load, controllable via the web. The following is a picture of the results of the power limiter trial via the web.

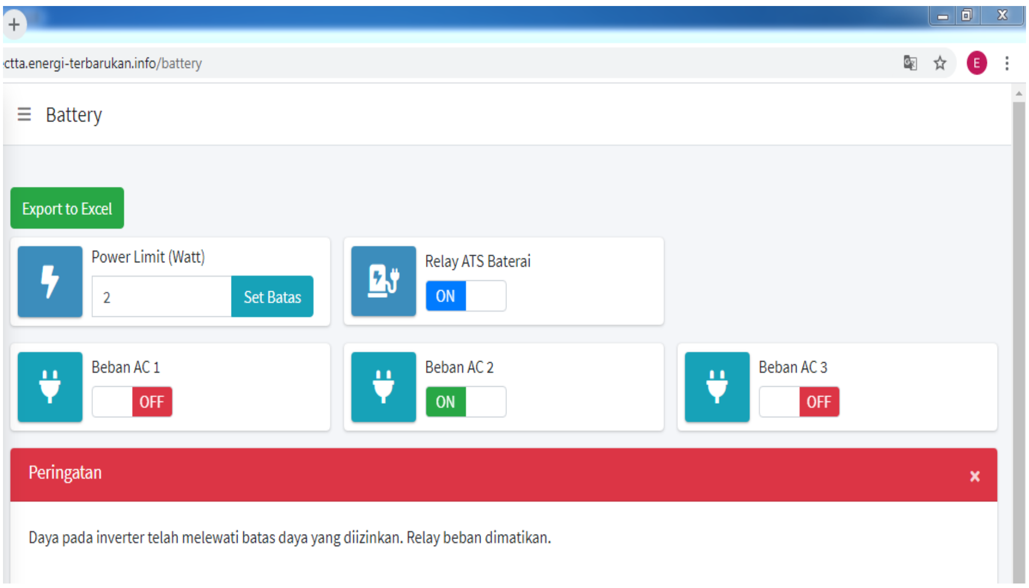

Figure 8. Testing Power Limiter

4. CONCLUSION

The research highlights the potential of solar energy as a sustainable alternative to non-renewable sources, particularly in equatorial regions with abundant sunlight. Solar cells convert sunlight into electrical energy, requiring batteries to store this energy efficiently. Proper battery management is crucial as continuous depletion can shorten battery lifespan. Technological advancements have automated tasks like data recording, enhancing efficiency and speed. Real-time monitoring of solar panel output parameters (current, voltage, power, and light intensity) is essential for performance assessment and optimization. The developed prototype system meets its design specifications, recording data in real-time and displaying it on a website as graphs and tables. It includes functionalities for AC load control and power limiting based on user commands, ensuring efficient energy usage. During tests, a 10 Wp solar panel achieved maximum performance around noon in sunny conditions, with light intensity above 50,000 Lux and currents up to 0.45 Ampere. However, the efficiency of 12.16% indicates room for improvement. This study demonstrates the advantages of automated, real-time monitoring and control in enhancing the performance and efficiency of solar power systems

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