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Design, Development, and Deployment of an IoT-Enabled Solar Energy Meter

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Abstract: This research paper explains the structural design, implementation and working process of an IoT-based Energy Meter for solar energy measurement with the ESP32 microcontroller and using the Blynk 2.0 application. The project makes the use of frequency of electricity consumption being monitored artificially with the help of the technology of IoT which proves to be much more efficient and consistent. The meter includes a current (SCT-013) and a voltage (ZMPT101B) sensor that provides data on voltage, current, real-time power consumption, and total consumed energy at all times. The data is then sent to a user-friendly dashboard via Blynk server which allows the system to be remotely accessed and monitored. As for continuous data logging, EEPROM storage was implemented on the ESP32 to make the logging possible even during constant power outages.The Esp32 and Blynk 2.0 platforms have been found to offer comprehensive real-time energy information gathering and analysis. The detailed accuracy and reliability of the system provide a less costly technique to monitor and manage the output of the solar energy application. There is a need for further improvement of the energy efficiency of the building including; RPA and the integration of prediction and forecasting algorithms into the system for energy management. This research paper demonstrates how IoT technologies can be applied to improve the efficiency and reliability of energy monitoring systems in general and specifically in the context of solar energy.

Keywords: IoT Energy Meter; Solar Energy Measurement; ESP32 Microcontroller; Blynk 2.0 Application; Real-time Monitoring.

1. Introduction

Energy consumption monitoring is equally important for both residential as well as commercial solar energy systems for enhanced efficiency [1]. The increased use of solar energy has made it evident that more complex methods of controlling energy consumption are required. Manual readings of energy meters are both labor-intensive and inefficient IoT provides the most effective solution to these issues by automating the gathering and analyzing of energy data [2]. IoT technology helps to create smart systems that accurately record energy consumption details in real time. With the help of IoT, it also becomes possible to monitor energy consumption, track any abnormalities, and adjust the energy supply in real-time. This is especially advantageous for solar energy systems where there is greater variability in the production and consumption of energy [3].

The purpose of this paper is to establish an IoT-based energy meter using an ESP32 microcontroller and the Blynk application. The ESP32 is chosen for its powerful processing capabilities and ease of integration with various sensor and IoT platforms. Blynk 2.0 is chosen as the application platform because of its intuitive interface, real-time visualization, and cloud infrastructure architecture that facilitates remote monitoring and control. The IoT based Energy Meter will use the SCT013 current sensor and the ZMPT101B voltage sensor to read the voltage, current, active power, and total consumption of electricity. These sensors are accurate and reliable thus making them suitable for energy monitoring. Another interesting feature of the SCT-013 is that it is a non-contact sensor that does not require physical contact with the wires to measure current allowing for a safer and easier installation. The ZMPT101B voltage sensor on the other hand allows precise measurement of AC voltage that is required for power calculations. Another important characteristic of this system is that it can sustain power failures. This is achieved by saving the energy consumption data in the EEPROM memory of the ESP32 microcontroller. EEPROM is the type of memory that enables the data to be stored even when the system is turned off and does not lose the values regarding energy consumption. This feature is particularly crucial in cases where power reliability can be an issue as this feature ensures that the monitoring process is always continuous and there are no missing data. The combination of these technologies produces a complete energy monitoring system that not only tracks and registers energy consumption but also gives interpretations via the Blynk 2.0 application dashboard. Users can view energy consumption trends in real time and detect anomalies that cause waste using their smartphone or web browser. Also, the system can send reminders in case of abnormalities or excessive consumption to control energy consumption.

1.1. IoT in Energy Management

The focus on the application of the IoT in the field of energy management is on the improvement of energy consumption monitoring efficiency and accuracy. Researchers like [4] pointed out the advantages of smart grid technologies which are based significantly on the huge power of IoT for real-time monitoring and control and its ability for efficient energy consumption and cost saving. An article by [5] about the benefits of IoT for the creation of smart environments puts stress on its role in the automatic measurement of energy data and presenting a high level of details of consumption.

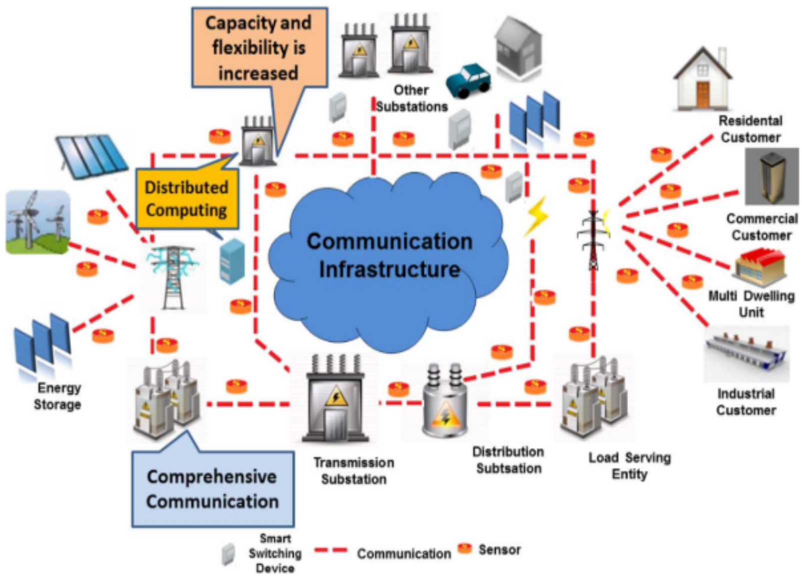

Figure 1. Smart grid boosts network capacity, flexibility [4]

1.2. Smart Energy Meters

Energy meters are the key components of contemporary energy smart systems. These meters as claimed by [6] will give real-time energy usage and facilitate billing and load management. They also enable the adoption of renewable energy technologies like solar power and give very accurate data on energy generation and consumption.

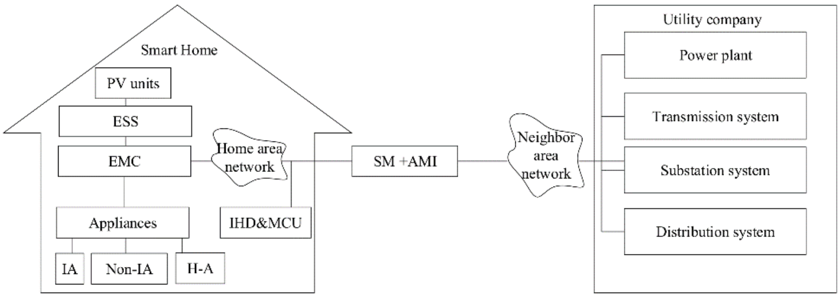

Figure 2. Creating a Comprehensive Energy Management Framework [6]

1.3. Solar Energy Measurement

Solar-based power generation measurement is difficult because of varying solar energy production. People have conducted many experiments to find valid methods for energy measurement of solar energy. [7] Developed an efficient integrated system for evaluating solar energy using sensors and IoT networks which shows the performance of elevated accuracy and reliability. However, the study by [8] made it clear how IoT system integration with solar energy systems shows how it can be beneficial for performance analysis and predictive failure analysis to minimize downtime and improve performance.

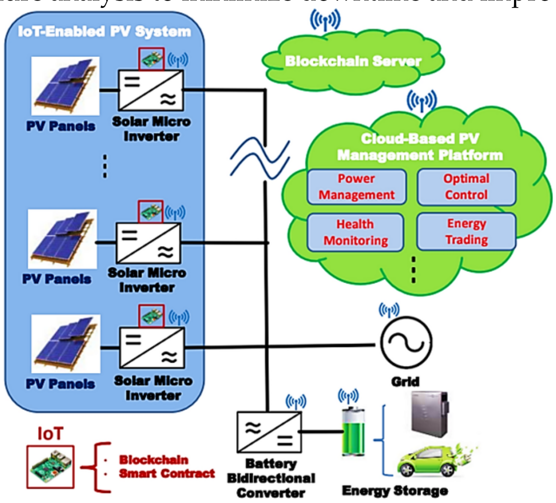

Figure 3. A State-of-the-Art Review on the Integration of Internet of Things with Solar Energy Applications [7]

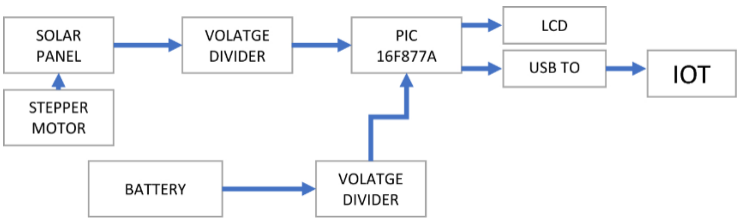

Figure 4. The Comprehensive Architecture of Model [7]

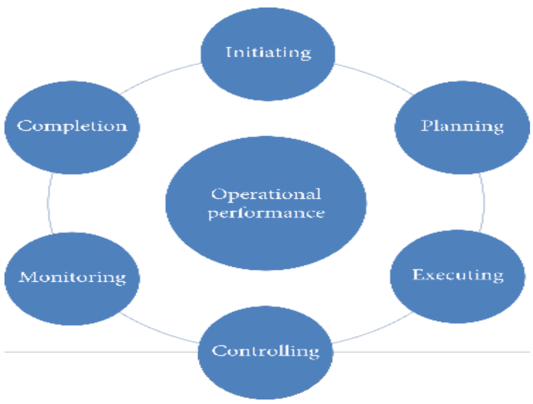

Figure 5. Operational performances [8]

1.4. ESP32 and Sensor Integration

The ESP32 is among the most ideal microcontrollers for IoT devices because of its powerful processor and inbuilt WIFI. [9] Analyzed the capabilities of ESP32 in IoT projects and stated that the board is easy to use with a wide range of sensors. The SCT-013 current sensor and the ZMPT101B voltage sensor are suitable for most IoT energy meters. [10] Implemented and explained that these sensors are accurate and reliable and can be used for energy monitoring concerns.

Figure 6. Implementation of energy management sensors [10]

1.5. Data Persistence and Reliability

Power failure is one of the reasons why the monitoring of energy is highly essential. EEPROM memories have been extensively discussed in the literature for their application in microcontroller-based systems for data storage. [11] showed that EEPROM also plays a very pivotal role in maintaining data during power failure to facilitate continued monitoring and logging.

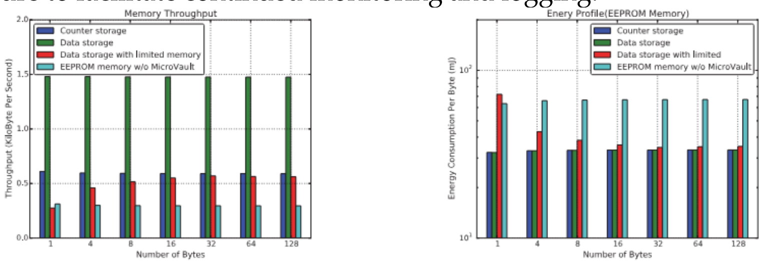

Figure 7. EEPROM Profile [11]

1.6. Blynk Platform

Blynk platform is often involved in IoT projects due to the ease of use and the reliable cloud infrastructure. [12] analyzed the features of a number of IoT platforms that are useful for real-time data visualization and remote monitoring and found that Blynk is the best for the given purpose. Its compatibility with ESP32 and similar MCUs makes it the perfect platform to create smart energy meter devices.

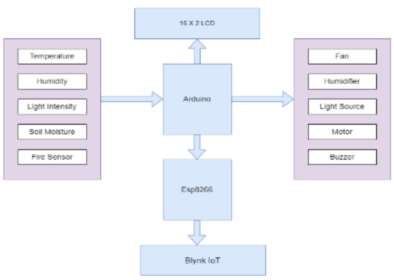

Figure 8. Block Diagram of proposed system of [12]

2. Materials and Methods

This section presents the details of the components, sensor specifications, circuit design, the software used, process of calibration, and method adopted for data logging and display in the development of the IoT based Energy Meter.

Table 1. List of Components

S.N.	Components	Quantity
1	ESP32 WiFi Module	1

2	ZMPT101B AC Voltage Sensor Module	1
3	SCT-013-030 Non-invasive AC Current Sensor	1
4	20x4 I2C LCD Display	1
5	Micro-USB Cable	1
6	Resistor 10K	2
7	Resistor 100Ω	1
8	Capacitor 10μF	1
9	Connecting Wires	10
10	Breadboard	1

The main components that were used to build the energy meter include the following. The most important component of the system is the ESP32 WiFi Module which performs computations and offers the WiFi function. For AC voltage measurement was carried out using the ZMPT101B AC Voltage Sensor Module while the SCT-013-030 Non-invasive AC Current Sensor was used for current measurement. A 20x4 I2C LCD Display was added to display actual energy in real time. Also, a micro-USB cable is used to power the ESP32 and upload the code. Signal conditioning components include two 10k ohm resistors, a 100-ohm resistor, and a 10-microfarad capacitor. Jumpers and a breadboard were used for constructing the prototype of the circuit.

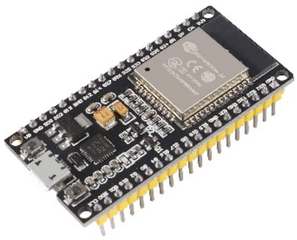

Figure 9. Nodemcu ESP32 Microcontroller WiFi & Bluetooth

Figure 10. SCT-013 Current Sensor

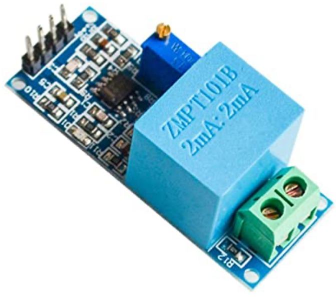

Figure 11. ZMPT101B AC Single Phase Voltage Sensor

The SCT-013 current sensor specifications include an input current range of 0-30A AC, a DC output signal of 0-1 V, a non-linearity of 2-3%, a turn ratio of 1800:1, and a dielectric strength of 1000 V AC for 1 minute at 5 mA. The ZMPT101B voltage sensor operates within the voltage range of up to 250V; a temperature range of -40ºC to +70ºC; and a supply voltage range between 5V and 30V.

The SCT-013 current sensor and the ZMPT101B voltage sensor are placed in the circuit and connected to the ESP32 microcontroller. The SCT-013 is connected to pin GPIO34 and the ZMPT101B is connected to pin GPIO35. The 20x4 I2C LCD is then connected to the 5V supply, ground, GPIO21 (SDA), and GPIO22

(SCL) of ESP32 to display the real-time readings. VCC and GND pins of both sensors are connected to the 5V and GND pins of ESP32. To create signal connections, I attached the output pin of the SCT-013 current sensor to GPIO34 and the ZMPT101B voltage sensor to GPIO35. Other extra components are 10K resistors employed for signal conditioning between the sensors and the ESP32 inputs and a 100Ω resistor connected in parallel with a 10μF capacitor to ensure the stability of the power supply and signal.

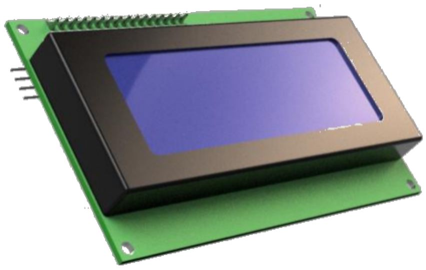

Figure 12. 20x4 I2C LCD Display

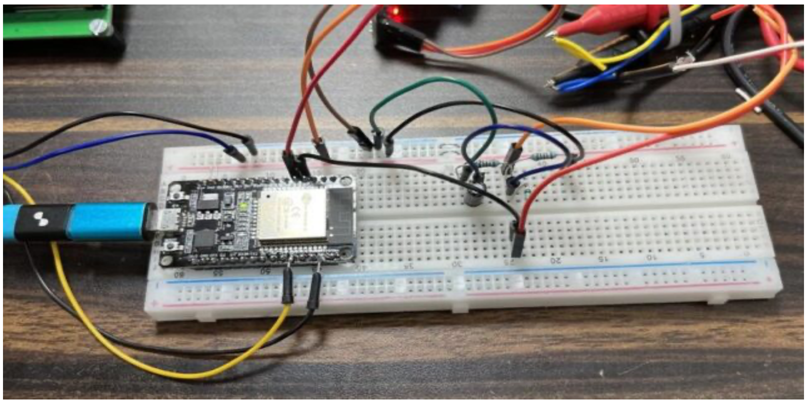

Figure 13. Sensors connectivity with Microcontroller

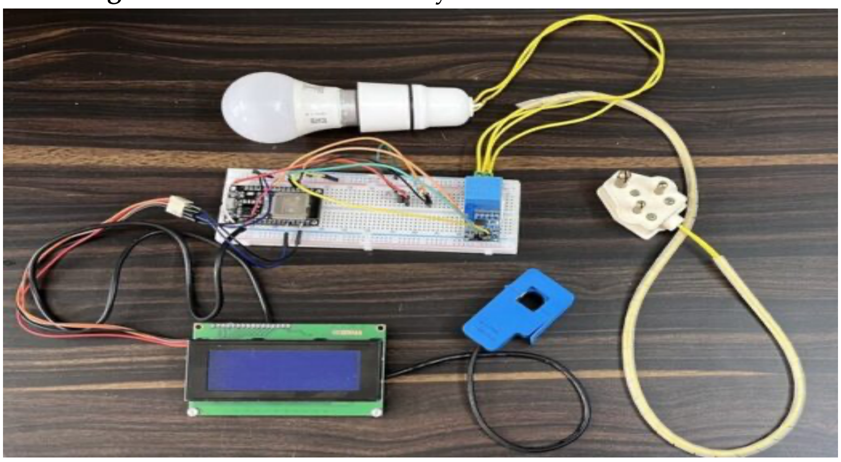

Figure 14. Complete Prototype

To program the Energy Meter, the Arduino IDE was used together with several libraries that were crucial to attaining functionality. The EmonLib library enables recording and calculating electric voltage, current, and power. The EEPROM library is used for data storage to maintain the data stored on it in case of power failure. WiFi and Blynk libraries are used to connect each of the devices to a remote dashboard. The programming process requires the installation of these libraries in Arduino IDE, the input of WiFi credentials and the Blynk authentication token in the code, and uploading the code to the ESP32 board.

Calibration is the most important step for the right measurements [13], especially for the ZMPT101B voltage sensor. This will need initial calibration using Arduino UNO. It includes connecting the ZMPT101B to one of Arduino UNO board analog pins doing a simple software for displaying analog values and changing the on-board potentiometer value until the numbers are the same as the expected voltage one.

The sensor is then calibrated and then incorporated with its setup to ensure that voltage readings are accurate.

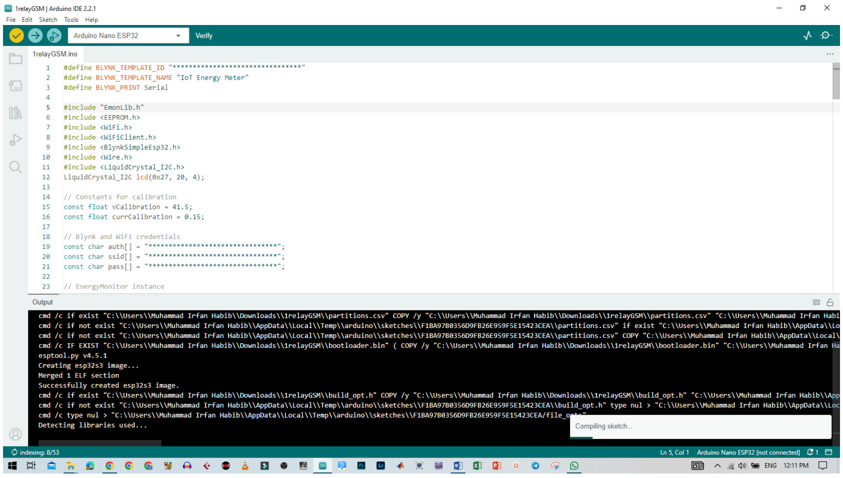

Figure 15. Microcontroller Programming

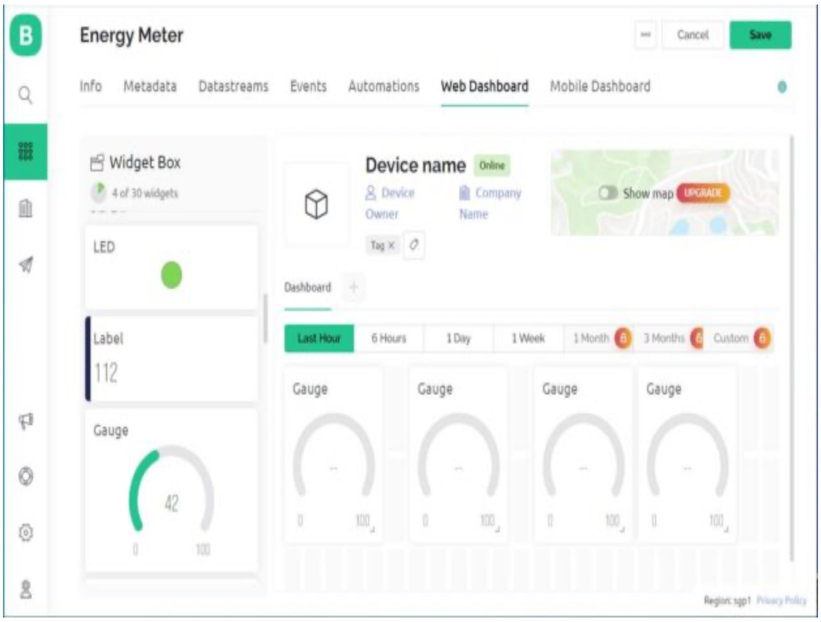

Figure 16. blynk.io Web Deshboard Settings

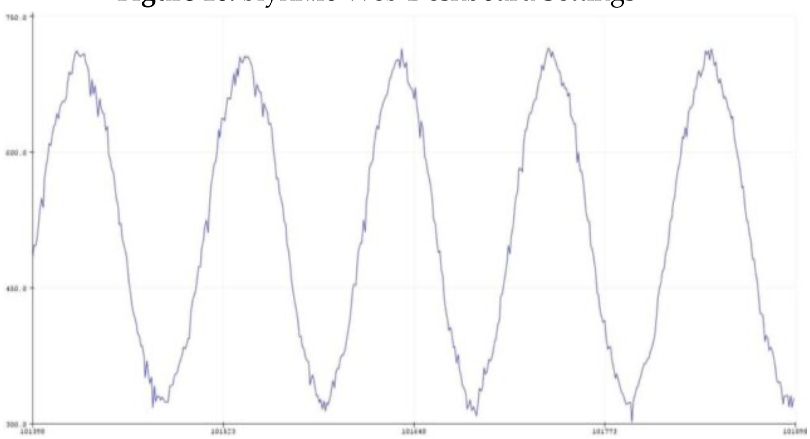

Figure 17. Serial Plotter output to do proper calibration

The system records actual values of voltage, current, power, and energy consumption periodically shows this data in the 20×4 I2C LCD, and sends this data to the Blynk application for remote control. Even if the power is cut, the last recorded values are saved in memory in the EEPROM of the ESP32 so that the system can continue to log after the power is turned on again. This is a perfect system that can be used to continuously monitor the electricity consumption of solar systems and effectively provide accurate results.

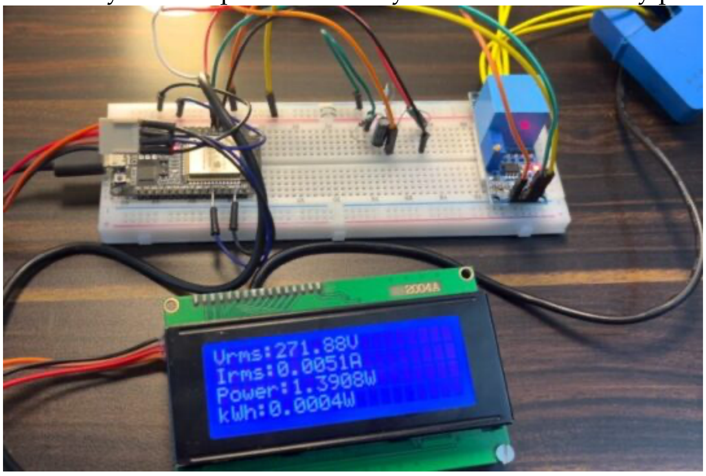

Figure 18. Energy Consumption

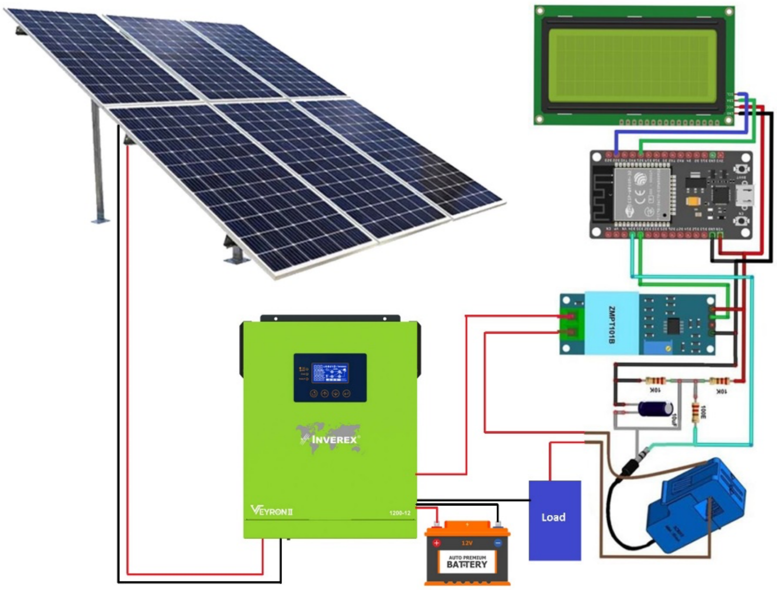

Figure 19. Complete System Schematic and connection diagram

3. Results

The IoT-based Energy Meterhas shown that the energy meter has been accomplished in measuring and recording voltage, current, power, and total energy use. They are divided into four depending on the system's main components and usage efficiency.

3.1. Accuracy of Measurements

The calibration was very instrumental in ensuring that precise measurements were made from the AC voltage sensor ZMPT101B and the current sensor of the SCT-013-030. Upon fine-tuning, the results of the voltage sensor showed that the voltage readings were both higher and lower than the standard multi-meter by a mere 1%. Also, the current sensor presented a small percentage of error; meaning that the current intensity measured by the current sensor differed by not more than 0-30 AC2% from the actual current intensity. These are critical for calculations involved in power and energy consumption.

3.2. Real-Time Data Monitoring

The integration it was achieved through the Blynk 2.0 Application designed to enable real-time tracking of all relevant metrics. Consumers could access voltage; current; power as well as total energy consumption on the web dashboard and Smartphone. It was regularly updated, especially the data being provided to the users at the end. The authors of [14] research determined the usefulness of the Blynk dashboard in monitoring and control, this dashboard was easy to use, responsive, and effective to monitor from a distance. In the same context an article by [15] states in the same context regarding the Right Content Management System for apps like blynk [16].

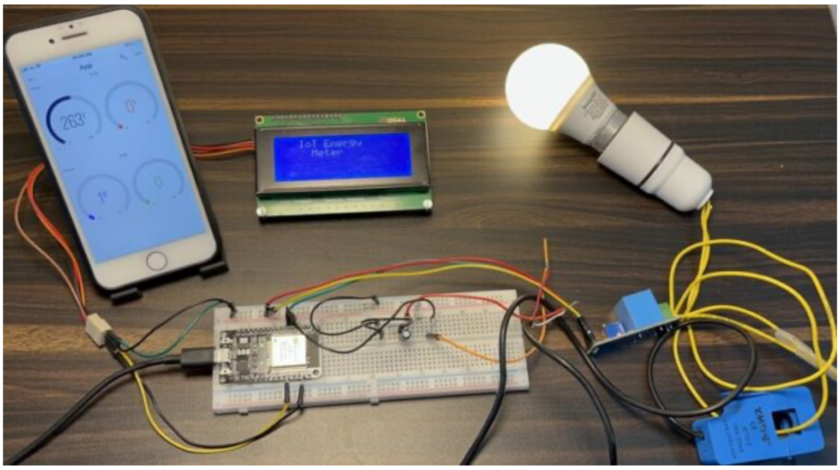

Figure 20. Accuracy of Measurements

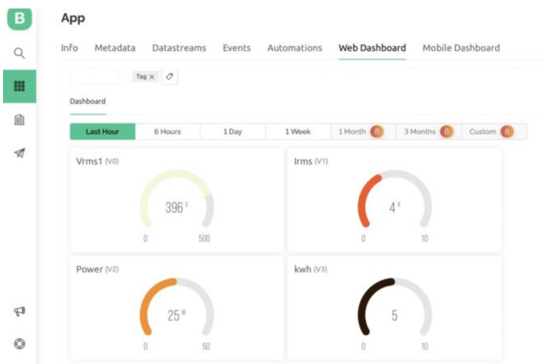

Figure 21. Real-Time Data Monitoring

3.3. System Stability and Performance

System stability and reliability were determined by testing the performance of the system under different load conditions. Here, whenever there occurred transitional changes in the load, the energy meter recorded expected and constant readings. The ESP32 microcontroller and the EmonLib library operated well with the data collected from the sensors and functioned smoothly without a significant amount of lag time or performance issues. This stability is critical to applications that necessitate monitoring in an uninterrupted and precise manner like domestic and commercial solar power systems.

3.4. Data Persistence and Reliability

To test the data persistence capabilities of the ESP32, simulated power outages were enacted to test the readability of the EEPROM storage. Before the power out, the system registered the current values and wrote them in EEPROM. When the power was turned back on the system was able to read the EEPROM memory and resume recording all of the data successfully. This feature means that the energy consumption data will not be lost during power outages and failure to monitor the system.

3.5. Overall System Efficiency

The combination of accurate sensors, above-average data logging capabilities, and live monitoring with the help of the Blynk2.0 app allows for achieving much more precise and reliable measurement results compared to the rest of the existing model's platform led to a very effective energy metering solution. Some functions of the system are aimed at simplifying and automating the process of monitoring: the data on the quantity of the fluid in the system are recorded automatically and there is no need for manual readings of the meters. The employment of IoT technology for accessing remotely the data about energy usage contributes to the improvement of user convenience and helps to enhance the coherence of energy management.

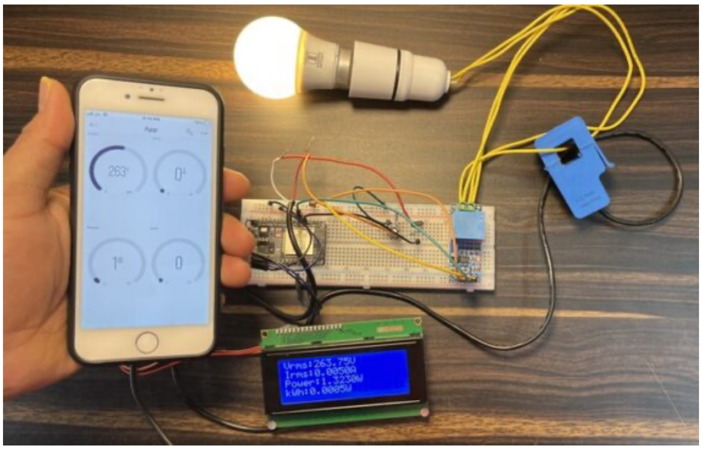

Figure 22. System Accuracy and Reliability

3.6. User Interface and Accessibility

The LCD was very important since it allowed real-time display of images on the device. This feature was particularly useful in initial setup and calibration because a quick verification output sensor could be performed. Moreover, the system setup and customization on the Blynk application were not difficult for users to operate due to its user-friendly interface and interactive dashboard configuration settings. The addition of support for web and mobile platforms guarantees users' ability to view their energy data company-wide, supporting the efficiency and practicality of the system.

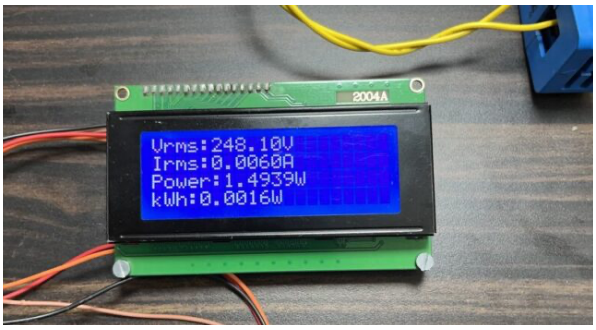

Figure 23. User Interface and Accessibility

Table 2. Real-time data displayed on both the LCD and the Blynk application

S.N.	Parameter	LCD Display	Blynk App
1	Voltage (Vrms)	230V	229V
2	Current (Irms)	5.00A	4.98A
3	Power	1150W	1145W
4	Energy (kWh)	1.50kWh	1.48kWh

4. Discussion

Design of an IoT-Based Energy Meter for Solar Cell measurement Using ESP32 Microcontroller and the Blynk 2. 0 platform offer unprecedented development of the work with energy systems in the aspect of their monitoring and management. This system provides immediate data gathering and information which is vital in the reduction of energy utilization. The use of capacitive touch sensors and the precise detection of the ZMPT101B AC voltage sensor and the SCT-013-030 current sensor provide accurate measures of voltage, current, power, and total energy consumption. These accurate readings are very essential for managing energy consumption effectively towards its optimum efficiency. Because the ESP32 microcontroller comes with WiFi, the means for data transmission are guaranteed to be reliable; as for the

Blynk part, the programmable buttons and displays are pretty stable as well. 0 application ensures that the remote monitoring is simple and uses the system better than the previous one. With its flexibility and scalability based on IoT and the energy meter concept, this meter can be applied in other contexts: commercial solar systems or industrial use. But as it is some challenges still exist some of which include ensuring that the data comes in securely and the initial setup and calibration of the sensors. However, modern technologies such as encryption and secure authentication for energy are required to ensure energy security and data integrity. The calibration of sensors is a time-consuming process, though, it is important for the overall system performance. It will take time for this system to completely evolve given that incorporation of predictive analytics and artificial intelligence into this system will be very beneficial to the system. Advanced systems can predict energy consumption using historical data to optimize usage ahead of time. ML might also be useful in an area such as predictive maintenance so that problems might be identified before they arise and become serious issues that threaten the design's overall operability. Moreover, there is the possibility of enhancing renewable energy forecasting by integrating weather prediction and solar irradiance forecast capability to assist users and producers in optimal planning of energy consumption and storage. Real-time energy monitoring contributes significantly to energy management because it provides insights into the most inefficient areas and thus provides an opportunity to take immediate action. For solar energy systems, this means that as much solar power as possible is utilized and as little as possible is dependent on the grid and this results in savings in terms of cost and also creates a desired effect on the environment. The energy meter would reveal specific details that would teach the users how to consume energy most effectively and sustainably, promoting the growth of sustainability efforts and the goal to cut down energy consumption and even help save the environment.

5. Conclusions

Energy Meter based on the Internet of Things Using ESP32 and Blynk 2. It has been proven that 0 can automate the process of electricity consumption and provides a wide range of benefits in comparison to traditional approaches. This system ensures real-time collection of accurate data on voltage, current power: and total energy consumption. The use of quality and reliable sensors such as the ZMPT101B voltage sensor and the SCT-013-030 current sensor helps in the precision of the system. One of the main benefits of this energy meter is the opportunity to control the device remotely through the Blynk application 2. 0 application enables the users to monitor their energy usage from anywhere if they have internet access. This feature greatly increases user convenience and enables them to make more proactive decisions regarding their energy use. Moreover, the system can perform continuous data logging even during power failures – the ESP32 has special EEPROM memory for data logging which can keep data integrity and reliability. The implementation of this energy meter shows that IoT technologies could be effectively used in improving the efficiency and reliability of energy monitoring systems including in solar energy applications. The system can collect data and deliver insight to the user immediately and aid them in regulating their energy consumption and waste as well as saving them money through better energy consumption. There are also opportunities for further development with this energy meter, including the addition of predictive analytics and machine learning models to increase energy utilization efficiency and optimize consumption estimates. All in all, the presented IoT-based energy meter is positioned as a great energy consumption monitoring solution. It's tracking speed and accuracy, real-time capabilities, and remote access enhancements provide effectiveness in both residential and commercial solar power. The energy meter became a success and one can say that IoT is the way to more sustainable and efficient energy use in the future.

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