IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

SMART ENERGY METER WITH REAL-TIME MONITORING AND PREDICTIVE BILL ANALYSIS

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Abstract: In this paper, We came with the Smart energy meter, With energy management taking center stage, the traditional energy meter does much less in providing instant data about power consumption. Smart Energy Meter with Real-Time Monitoring and predictive bill calculation, is designed and implemented based on the ESP32 microcontroller. The system consists of a PZEM-004T energy meter for the measurement of total power, ACS712 current sensors for the monitoring of individual loads, and a DHT11 sensor for the monitoring of environmental parameters. Remote load control is done through a 4-channel relay module, while real-time energy data is made available on a 16x2 I2C LCD display as well as uploaded to the Thingspeak platform, where it can be downloaded in .csv file format. The smart meter continuously measures voltage, current, power and energy consumption while also calculating the predictive billing on the basis of past trends. The data is locally displayed as well as the Blynk IoT platform, which gives users the ability to monitor energy usage and control loads remotely. This proposed design thus raises awareness among consumers, maximizing energy efficiency, and providing a cost-effective solution to home automation.

Index Terms - Smart Energy Meter, ESP32, PZEM-004T, ACS712, Real-time Monitoring, Predictive Bill Analysis, IoT, Home Automation, Blynk .

1.INTRODUCTION

Real-time monitoring, predictive bill analysis, and remote load control in the application of an IoT-based Smart Energy Meter to remove the limitations faced in traditional energy metering systems. Hence the system comprises an ESP32 microcontroller interfacing with a PZEM-004T energy meter to comprehensively measure power, while ACS712 current sensors do the load monitoring individually. Environmental parameters are acquired through a DHT11 sensor for measuring temperature and humidity; there is control of the appliances through a 4-channel relay module. There is a 16x2 I2C LCD to display feedback immediately to the user at the installation site.

Connectivity to the cloud via the Blynk platform permits users to view power consumption values remotely. The predictive bill analysis functions on this system estimate the electrical bill for a time period in the future based on historical usage patterns, informing the consumer on how to consume energy wisely. Moreover, users are notified via threshold-based alerts when energy use exceeds a set limit, thereby encouraging proactive energy management.

The smart energy solution motivates high efficiency, cost reduction, and sustainable electricity consumption via six specific objectives: real-time energy monitoring, predictive bill analysis, remote load control, user-friendly display interfaces, threshold-based alerting systems, and home automation integration. The need for this research is especially timely, owing to the ever-increasing global campaign on energy efficiency, sustainability, and low costs. Such a practical solution would immensely benefit cases of unexpected elevated electricity bills, while also contributing to global sustainability in promoting optimized consumption of energy.

1.1 Objective

This project on smart energy meters has the following aims: to implement an online energy monitoring using PZEM-004T and ACS712 sensors for measurement of voltage, current, power, and consumption; develop future bill prediction on potential electricity prices based on historical trend estimations; enable remote load controlling advantage on the Blynk platform; provide feedback to the user through a 16x2 I2C LCD display; implement threshold-based alerts for user notification when consumption exceeds certain limits; and integrate home automated systems for intelligent load control through relays, depending on the above features, so that the entire electricity consumption is transparent, energy-efficient, and cost-effective for modern-day electric monitoring.

2. METHODOLOGY

This project's methodology consists in the gradual development and implementation of the Smart Energy Meter system, performing real-time monitoring, predictive bill analysis, and remote control based on IoT technologies. Its main purpose was to design a reliable and user-friendly energy monitoring solution, enabling consumers with insights into what happens to their energy consumption and at the same time control electrical appliances through a mobile application. The overall methodology was structured into three core stages: hardware integration, software implementation, and system validation.

The hardware design phase revolves around building the system through the ESP32 microcontroller serving as the central unit for data processing and communication. The PZEM-004T sensor is used for measuring total load parameters such as voltage, current transfer, power, and energy consumption, while four ACS712 current sensors are deployed for monitoring the individual current consumption of separate appliances. DHT11 sensor is further utilized in measuring environmental parameters such as temperature and humidity. To provide real-time local feedback to the user, a 16x2 LCD display with an I2C interface is to be used, and a 4-channel relay module is needed to manually or automatically switch certain connected electrical loads, such as bulbs and sockets.

For the software part, the ESP32 is programmed using the Arduino IDE, while the Blynk IoT platform is included for remote control and monitoring. ESP32 was Wi-Fi connected to the Internet allowing it to communicate with the Blynk server, sending sensor data and receiving user commands. Each parameter—voltage, current, power, energy, and temperature—was mapped to a virtual pin in the Blynk mobile app, displaying live readings for the user to visualize and control appliances from smartphone devices. Extensive testing was conducted on the assembled system for data accuracy, stability of the system, and reliable communication between the hardware and the cloud. The results prove that the system functioned as designed and that it can be a scalable and cost-effective solution for energy management at the household and small-scale.

2.2 Block Diagram

The block diagram of a smart energy meter representing system architecture, which is meant to record electrical parameter monitoring in real time, and remote control of individual electrical loads. The system receives its input from a standard 220V, 50Hz supply. This feeds into a PZEM-004T module measuring all voltage, current, power, and energy consumption in the connected circuit. The output from the PZEM-004T is further directed to the ESP32 microcontroller, which serves as a central data acquisition, processing, and communication unit.

Another arrangement comprised of four ACS712 current sensors connects separately between relays and loads for monitoring the current used per appliance. By doing this, each sensor will measure and keep track of the amount of energy the particular appliance will be draining, thus giving a precise individual reading on energy usage. The relay module is acting here in dual function: switching on and off the loads supply for power as well as cooperating with the ESP32 to switch the appliances ON-OFF as per the user input. Additional functionality is provided by a DHT11 sensor which can be integrated into the structure to measure ambient temperature and humidity around the energy monitoring procedure environment.

The processed data from the ESP32 would be transmitted to several output modules for user interaction. For instance, a 16x 2 I2C LCD display would be used to show the live readings from the meter locally. The device is then put into the Internet via the ESP32, which transmits the data to the Blynk mobile application for remote reading and control of energy load usage. The data can also be sent to a ThingSpeak channel or cloud server for long-term logging and analytics of data. A power supply unit keeps the ESP32 and all modules operating at the required voltage levels, effectively completing the hardware loop in this intelligent energy-monitoring system.

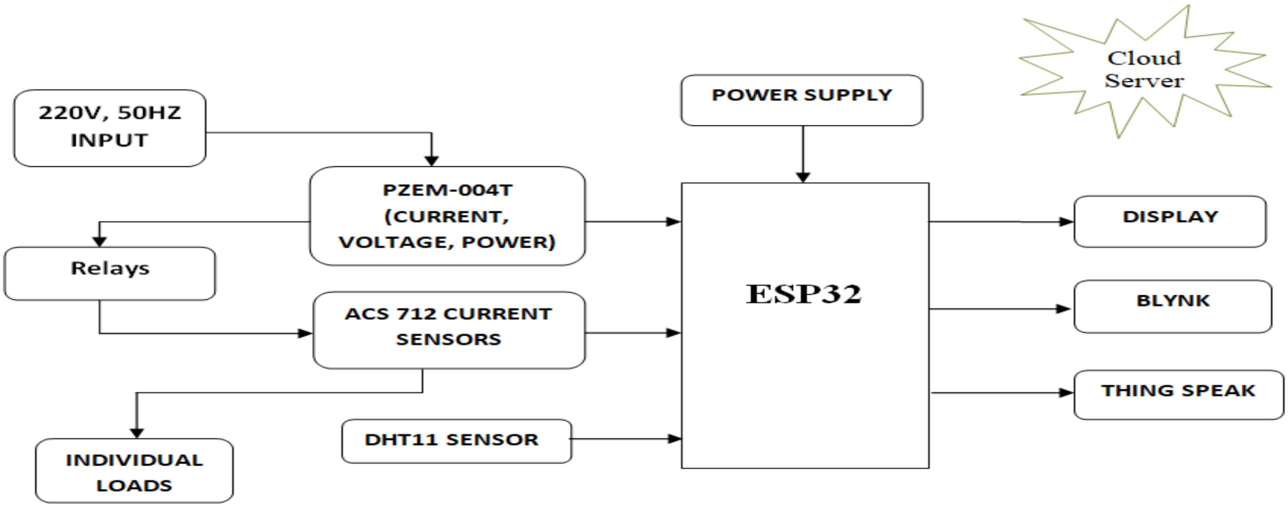

Fig 2.1 Block Diagram of smart energy meter

This modular nature of a system makes it very scalable and adaptable for different applications like the energy monitoring at home level and small-scale industries. Further increase in individually monitored loads can be craned by adding ACS712 sensors and relays, while the ESP32 supports connectivity for multiple protocols like I2C, UART, SPI, and Wi-Fi for easy interfacing with other sensors or modules. The use of IoT platforms such as Blynk and ThingSpeak provides real-time access to data from anywhere, thus promoting smart energy management and informed user decisions.

The Flow chart is as shown below,

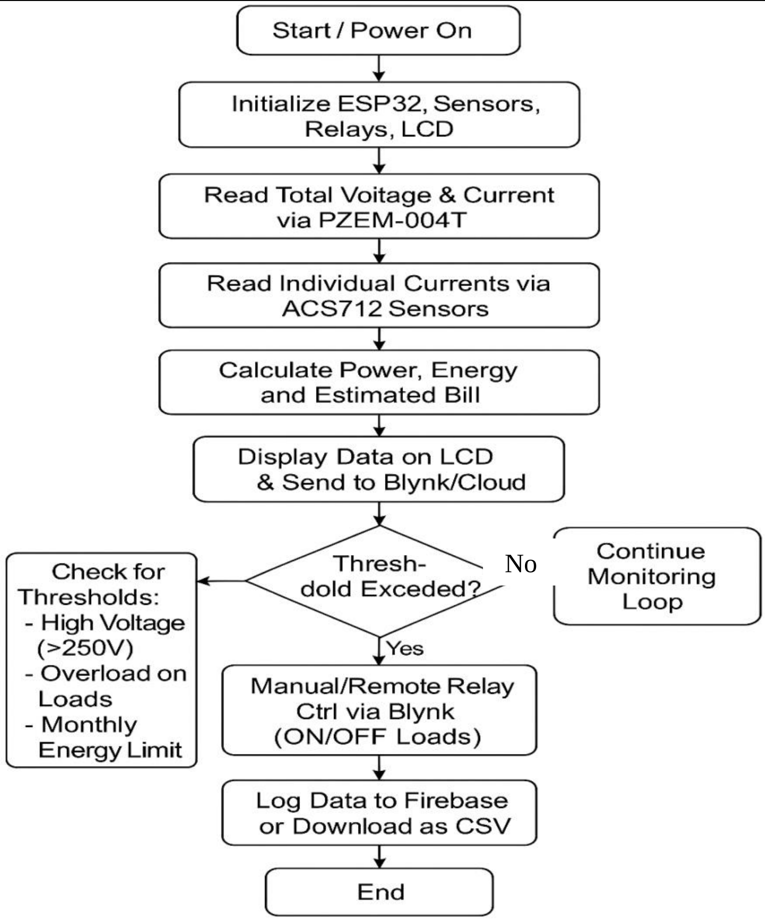

Fig 2.2 Flow Chart of Smart energy meter

3. Hardware Implementation

3.1 ESP32 Microcontroller:

The remarkably versatile dual-core ESP32 microcontroller includes integrated Wi-Fi and Bluetooth, making it most suited for IoT applications. Serving as the brain of the Smart Energy Meter system, it executes all sensor data acquisition, processing, and communication. Working with the Blynk IoT, it provides remote monitoring and control capabilities. Its powerful supply of digital and analog I/O pins and communication protocols like UART, I2C, and SPI make it easy for interfacing with various modules and sensors involved in this project.

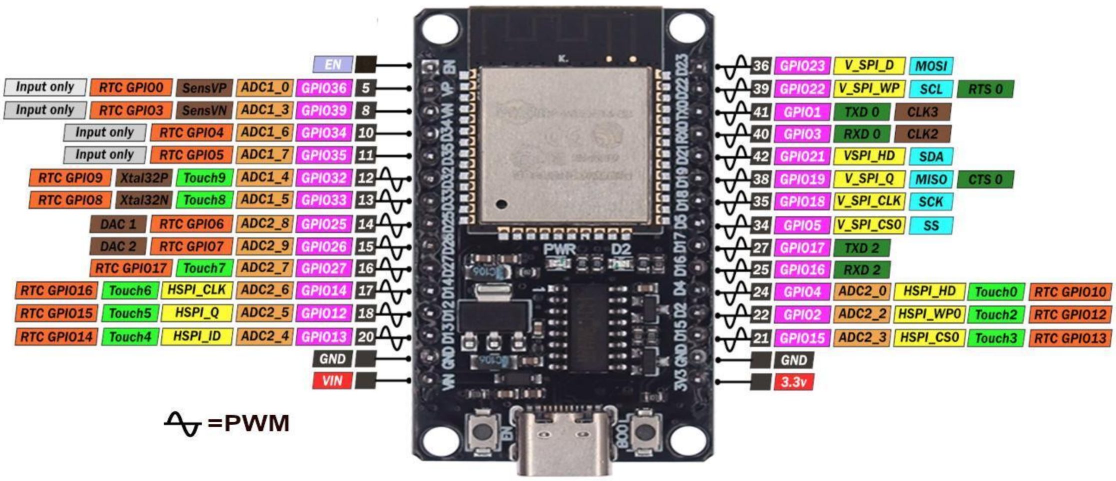

Fig 3.1 ESP32

3.2 PZEM-004T Energy Measurement Module:

The PZEM-004T Energy Meter module is responsible for measuring voltage, current, active power, energy consumption (kWh), frequency, and power factor. It is connected to the 220V AC main line and communicates with ESP32 via UART. The real-time energy monitoring offered by this module is a sine qua non for predictive billing and energy audit.

Fig 3.2 PZEM -004T Sensor

3.3 ACS712 Current Sensor:

The ACS712 is a Hall-effect-based sensor which is utilized to measure the individual current of appliances. It provides an analog voltage output, which is directly proportional to the current flow and is read by the ESP32 using its internal analog-to-digital converter. This project uses multiple ACS712 modules to monitor different loads separately for accurate load-wise analysis. Given its compact design and easy handling, it can easily be integrated into embedded energy systems.

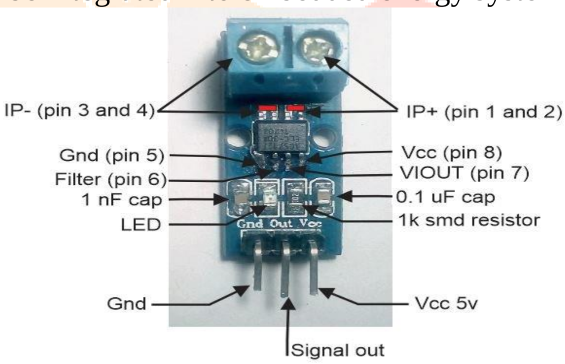

Fig 3.3 ACS-712 Current Sensor

3.4 4-Channel Relay Module:

The module is used to control four independent electrical appliances via the ESP32. Each relay serves as an electronically controlled switch so that the microcontroller can manage high-voltage AC devices while providing electrical isolation. The relays can be toggled manually from the Blynk mobile app, so that users are able to turn devices ON or OFF from a remote location. The relay module thus adds the home automation feature to the energy meter system.

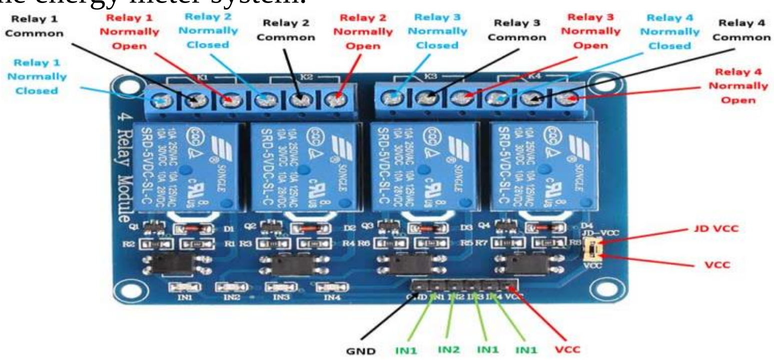

Fig 3.4 4-channel relay module

3.5 DHT11 Temperature and Humidity Sensor:

The DHT11 sensor measures ambient temperature and relative humidity to provide environmental context to the energy monitoring data. It transmits digital data directly interfaced with the ESP32. Integrating environmental monitoring into the system gives users additional data that may influence the use of appliances, for example using set speeds of fans or air conditioners dependent on room temperature.

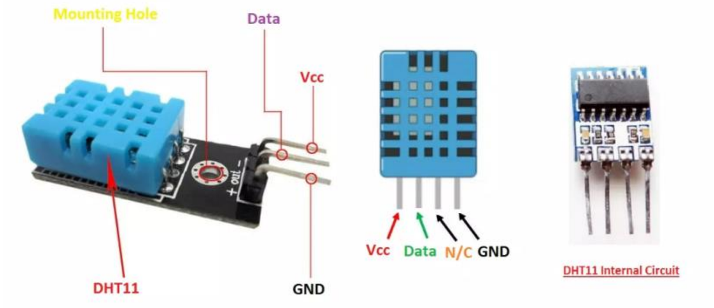

Fig 3.5 DHT11 Sensor

3.6 16x2 I2C LCD Display:

This display module is used to show live readings of voltage, current, power, energy, and temperature locally. The I2C interface significantly reduces wiring requirement, using only two data lines, thus fulfilling microcontroller projects. This enables real-time feedback offline, in the absence of Internet connectivity or mobile control.

Fig 3.6 16x2 I2C LCD Display

3.7 Power Supply Unit:

The power supply circuit converts 220V AC to the required 5V/3.3V DC needed to operate the ESP32 and its peripherals. Voltage regulator

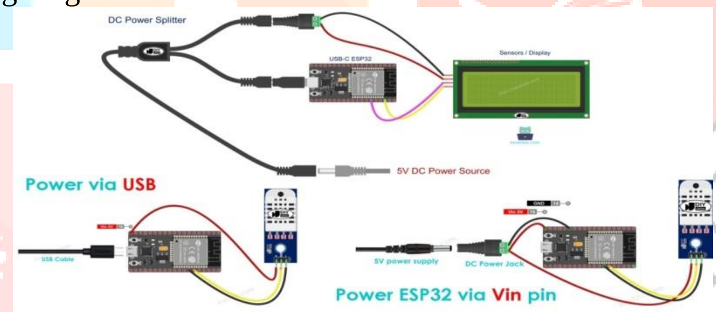

Fig 3.7 Power supply to ESP32

4. Working

The Smart Energy Meter system functions as an interfacing system that gives power to the ESP32 microcontroller and all its peripherals through the regulated supply. Electrical parameters such as voltage, current, power, energy consumption, frequency, and power factor are measured directly from the PZEM-004T module which connected to the 220V AC line. Meanwhile, ACS712 current sensors are also connected to individual loads for measurement of current drawn by each appliance separately. The values read are then calculated to get power consumed by each load by the ESP32 using the voltage reference from the PZEM module. Besides that, the environmental parameters are determined using the DHT11 sensor which can give temperature and humidity reading contextually to energy management.

The real-time display of the collected input from all the sensors is performed by the ESP32 on a 16x2 I2C LCD display after processing all sensor inputs. The Blynk IoT platform uses Wi-Fi to be able to interact real-time with a system on a mobile app. Thus, users are able to obtain real-time voltage, current, power, energy, and temperature readings straight to their smartphone application. Furthermore, the current system is equipped with a 4-channel relay module, so they can monitor and control the on-off state of individual appliances through the application. Hence, this ensures that most unnecessary loads can easily be switched off and energy use is maximized in a very efficient manner. Continuous data acquisition and two-way interaction keep the system responsive and efficient to use, while encouraging the desired behavioral change towards smart energy usage and savings.

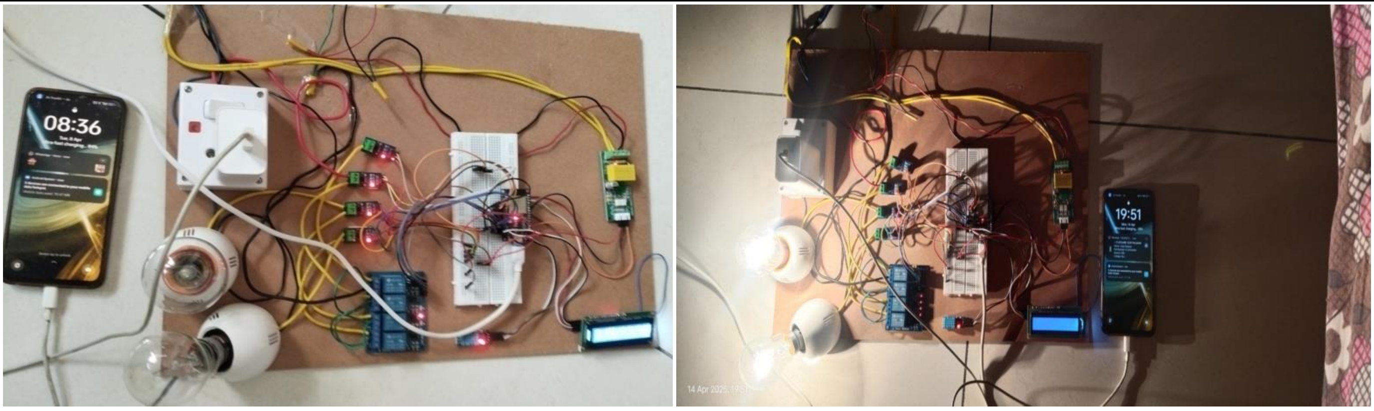

Fig 4.1 Hardware Kit

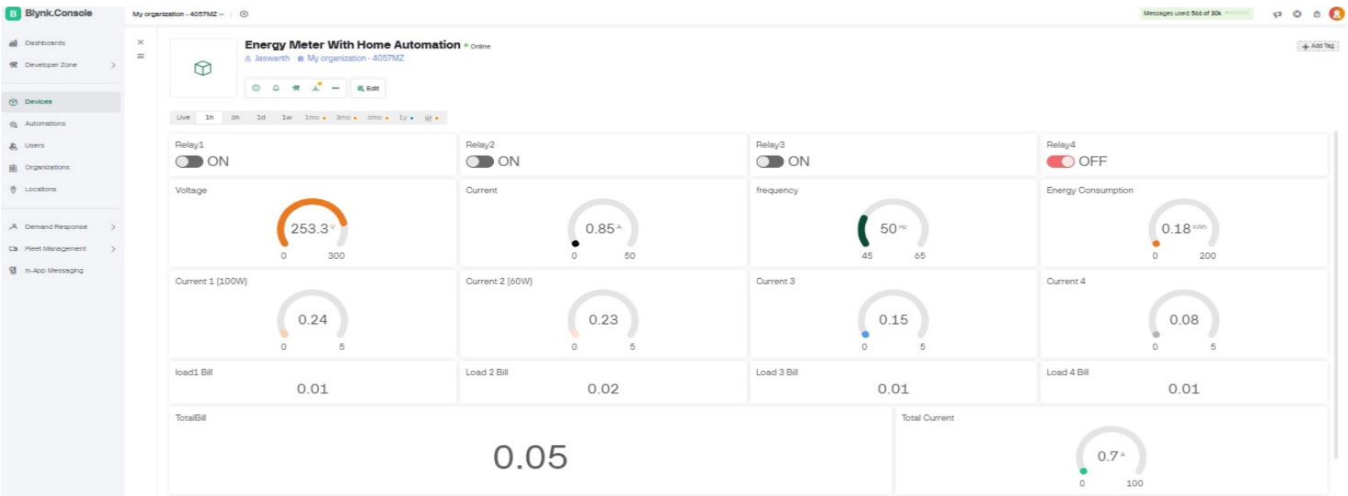

Fig 4.2 Blynk Output

2025-04-14T19:46:22+05:30	404	255.9	0.3	76.3	0.16	0.02	0.01	0.01	0
2025-04-14T19:46:48+05:30	405	256.1	0.3	76.3	0.16	0.02	0.01	0.01	0
2025-04-14T19:47:12+05:30	406	256.1	0.3	76.3	0.17	0.02	0.01	0.01	0
2025-04-14T19:47:38+05:30	407	256.1	0.3	76.3	0.17	0.03	0.01	0.01	0.01
2025-04-14T19:48:03+05:30	408	254.1	0.76	193.1	0.17	0.03	0.01	0.01	0.01
2025-04-14T19:48:27+05:30	409	255.6	0.15	23.8	0.17	0.03	0.01	0.01	0.01
2025-04-14T19:48:53+05:30	410	254	0.85	213.7	0.17	0.03	0.01	0.01	0.01
2025-04-14T19:49:17+05:30	411	253.9	0.85	213.7	0.17	0.03	0.01	0.01	0.01
2025-04-14T19:49:42+05:30	412	253.8	0.88	219.8	0.17	0.04	0.01	0.01	0.01
2025-04-14T19:50:07+05:30	413	253.8	0.85	213.5	0.17	0.04	0.01	0.01	0.01
2025-04-14T19:50:32+05:30	414	253.7	0.85	213.6	0.17	0.04	0.01	0.01	0.01
2025-04-14T19:50:57+05:30	415	253.4	0.87	217	0.18	0.04	0.01	0.01	0.01
2025-04-14T19:51:22+05:30	416	253.6	0.86	215.7	0.18	0.04	0.01	0.01	0.01
2025-04-14T19:51:47+05:30	417	253.4	0.85	213.6	0.18	0.04	0.01	0.02	0.01
2025-04-14T19:52:12+05:30	418	253.1	0.85	213.2	0.18	0.05	0.01	0.02	0.01
2025-04-14T19:52:37+05:30	419	253.3	0.85	213.5	0.18	0.05	0.01	0.02	0.01
2025-04-14T19:53:02+05:30	420	253.4	0.85	213.7	0.18	0.05	0.01	0.02	0.01

Fig 4.3 Excel Sheet values of different parameters

5. CONCLUSION

This Smart Energy Meter is able to accomplish the task of real-time monitoring, individual load tracking, and wireless control of appliances through an IoT-enabled system so efficiently. It uses an ESP32 microcontroller along with sensors like PZEM-004T, ACS712, and DHT11 to get accurate readings of voltage and current, power, energy consumed as well as environmental parameters. Actual data can be viewed simultaneously on a 16x2 I2C LCD and pushed to the Blynk IoT platform for access and possible load control via smartphone-both local and remote.

With this setup, the user gets total control over his energy usage, encourages energy-saving behavior, and insights about consumption trends. Looking ahead, the system is quite promising in terms of the path from further developments and upgrades for incorporation of features such as cloud-based data logging, AI energy savings suggestion systems, and real-time push notifications for enhancing user awareness and system intelligence.

The project could be extended to multi-phase industrial applications and mostly over-built assisted solar energy for green energy users. Integration of voice assistants like Google Assistant or Amazon Alexa would enable the hands-free operation of appliances using this system. Such improvements will make the system stronger and scalable while keeping an eye on the evolving trends of smart energy management and sustainable living.

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