Design and Implementation of a Smart Energy Meter System using the Internet of Things

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Abstract

Recent advances in the Internet of Things (IoT) and cloud computing have led to the development of various smart home applications and services. In addition, with the increase in the number of home appliances, the daily electricity consumption is also increasing, which increases the need for smart energy meters and monitoring systems. The proposed smart energy meter system measures current and voltage, calculates energy consumption and other information. The system is realized using ESP32s board (combination of microcontroller and Wi-Fi module), which connects to the internet and uploads data to the cloud. ThingSpeak is used as a cloud web server, which allows any user to remotely view individual consumption figures. This paper presents the design and implementation of a household smart energy meter that can collect and store energy consumption data of household appliances and major loads. The system measures three-phase currents and voltages, calculates power consumption, transmits the data to the cloud and displays it on an OLED screen.

Keywords:

Internet of Things, smart energy meter, ESP32s board.

Highlights:

- We present a comprehensive study on the development and implementation of a Smart Energy Meter with cloud connectivity.
- The system is built to measure current and voltage, calculate energy consumption, and seamlessly send the data to the cloud-based web server, ThingSpeak.
- The Smart Energy Meter presented in this paper represents a significant advancement in the field of energy monitoring. By harnessing the power of cloud connectivity, it offers a convenient and efficient solution for real-time energy consumption monitoring.

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1. Introduction

The Internet of Things (IoT) has grown rapidly in recent years. It is a network of connected devices that can be remotely controlled and monitored via the Internet. IoT is used in various fields including smart cities, smart homes, smart transportation, smart agriculture, smart energy, smart healthcare, and smart industry [1]. Figure 1 shows the components of a smart home. A smart home includes several IoT connected devices such as access detection system, motion detection system, irrigation system control and monitoring system, gas leak detection system, alarm control system and smart electricity meters [2]. The data collected in smart homes are uploaded to the cloud via the Internet and can be stored and displayed remotely on any user's PC or smartphone.

This study focuses on one of the applications and services of smart home - energy meters. Energy meters are an important aspect of the smart home concept [3]. The device measures the electricity consumption of various devices connected to the household power grid. A smart energy meter is an electronic device with a chip to measure electricity consumption, data transmission protocols, security features, interfaces for data display and other features [4]. The difference between smart energy meters and traditional meters is that smart meters can transmit data using advanced communication protocols [5]. Smart meters should be able to record real-time active power consumption and other information about the electronic device such as voltage and phase current, reactive power, maximum power consumption, frequency and power factor [6].

The Internet of Things (IoT) is defined by IERC as physical and virtual "things" with identity, physical attributes and virtual individuality, using intelligent interfaces and easily integrated into information networks based on standard, interoperable communication protocols. It is defined as a dynamic global network infrastructure with self-configuring capabilities [7]. Following the use of IoT to satisfy consumers, the development of smart meters utilizing devices and communication technologies is needed. This paper presents the design of a smart electricity meter that accurately measures and displays electricity consumption for consumers.

The main research contribution of this scientific paper, compared to previous studies, is the development of a system specifically designed for the measurement and management of three-phase electricity systems, which are commonly found in smart homes and smart buildings.

The content of this paper is organized as follows. After the introduction, Section 2 provides a review of related works. The materials and development methodology of the proposed system are summarized in Section 3. Section 4 details the experimental setup, actual implementation, performance analysis and results. Finally, Section 5 provides conclusions.

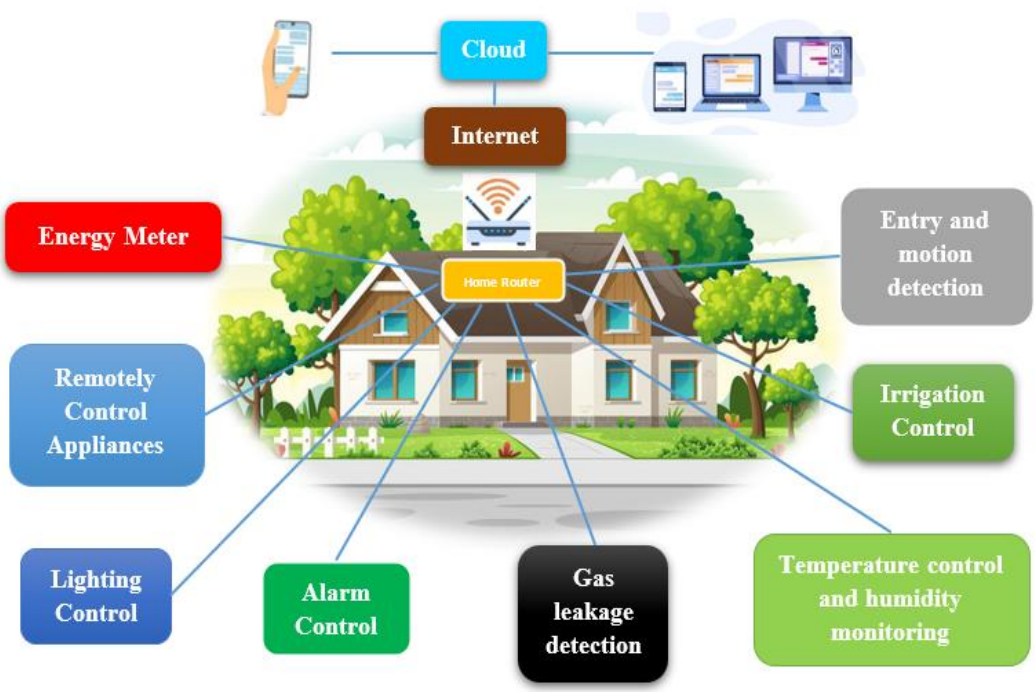


Figure 1. Smart Home Components

2. Related Work

Several studies have approached the problem of designing smart energy meters. Many studies have focused on the use of IoT-based meters; Omar Munoz et al [8] proposed an IoT smart meter with load control for home energy management systems. Their system was developed using a simple IoT architecture with built-in Wi-Fi technology that allows direct connection to the Internet and at the same time was large enough to be part of a standardized electrical enclosure. Mohammad Hossein Yaghmaee and Hossein Hejazi [9] designed and implemented a smart energy metering platform using IoT functionality consisting of a smart plug, gateway, and cloud server; Kashif Naseer Qureshi et al. studied. They proposed an Internet of Things (IoT) based energy management scheme for smart homes based on the deficiencies found in the reviewed projects. Their design includes a security mechanism that controls end-to-end communication and uses smart scheduling and time management of controllable and uncontrollable household loads to monitor and reduce energy consumption. M. Usman Saleem et al. in [11] developed a smart energy management system for smart environments that integrates an energy controller and an IoT middleware module. Each device is connected to an energy controller that incorporates a number of sensors and actuators into an IoT object, through various time slots designed to optimize the energy consumption of the air conditioning system based on ambient temperature conditions and building operational dynamics The energy consumption data is collected from the energy controller and communicated to a centralized middleware module (cloud server) for management, processing, and further analysis.

There seems to be quite a bit of research and development going on in the area of smart energy meters, especially in the area of IoT technology. Each of the studies you mentioned address different aspects of energy management and efficiency.

Omar Munoz et al. focus on load-controlled IoT smart meters, with an emphasis on simplicity and direct connection to the Internet. Mohammad Hossein Yaghmaee and Hossein Hejazi, on the other hand, implemented a platform incorporating smart plugs, gateways, and cloud servers for energy metering.

Kashif Naseer Qureshi et al. proposed an IoT-based energy management scheme for smart homes, addressing the shortcomings of existing projects by integrating security measures and intelligent scheduling to optimize energy consumption.

Finally, M. Usman Saleem et al. developed a comprehensive smart energy management system, incorporating demand-side management, energy controller, and IoT middleware to optimize energy use based on environmental conditions and building dynamics.

While extensive research has been conducted on smart energy meters, most existing studies primarily focus on single-phase measurements. However, there is a significant gap in the research regarding smart energy meters capable of accurately measuring and managing three-phase electricity systems. Three-phase systems are prevalent in smart homes, smart buildings industrial and commercial environments, and their efficient management is crucial for optimizing energy use and ensuring system reliability.

3. Materials and Methods

In this section, the proposed system is introduced in detail. Hence, the general system overview is presented, followed by the hardware and software components design.

3.1 System Architecture and Design

Smart energy meters have changed the way energy consumption is monitored and managed. They are proving to be a great resource for energy efficiency and sustainability. Smart energy meters provide real-time data on electricity consumption, allowing consumers to make informed decisions about their energy use. By tracking their usage habits, individuals can reduce their carbon footprint. In addition, smart meters enable accurate billing based on actual usage rather than estimated usage, ensuring consumers are billed fairly.

Furthermore, smart energy meters make renewable energy sources easier to integrate into the system. These gadgets, which can detect both the import and export of electricity, enable homeowners who have solar panels or wind turbines to sell their energy.

Figure 2 shows a block diagram of the proposed system. The system architecture consists of a microcontroller unit (MCU), a current sensor, a voltage sensor, an OLED display, and a Wi-Fi module to connect to the internet. The data collected from sensors is processed by the MCU, uploaded to the cloud web server via the internet, and displayed by the user.

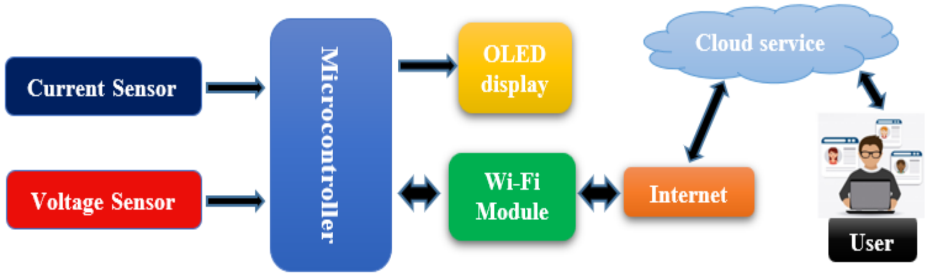


Figure 2. Block diagram of the smart energy meter

3.2 Hardware Components

To conduct this project, we need to use a microcontroller and a Wi-Fi module. The best choice for the IoT project is an ESP32s. It's an excellent tool for creating IoT projects. ESP32s have sufficient ADC (Analog to Digital Converter), and communication protocols such as I2C, SPI, and some other features.

The proposed system consists of the following components: an Esp32(NodeMCU-32S), a voltage sensor (ZMPT101B 2mA), a current sensor (SCT-013), and an OLED (128 x 64) display as shown in Figure 3.

a. Esp32(NodeMCU-32S)

The development of low-cost prototypes for the measurement and management of three-phase electricity systems is crucial for the advancement of smart home and smart building technologies. We compare the ESP32s board with the Arduino MKR WiFi 1010 and Arduino Nano ESP32 to demonstrate the superior suitability of the ESP32s for these applications. The ESP32s board is the most cost-effective option at $5-$10, compared to the Arduino MKR WiFi 1010 at $30-$40 and the Arduino Nano ESP32 at $15-$20. The ESP32s offers robust processing power and memory with a dual-core processor at 240 MHz and 520 KB of SRAM, surpassing the Arduino MKR WiFi 1010's SAMD21 Cortex-M0+ processor at 48 MHz and 32 KB of SRAM, while being comparable to the Arduino Nano ESP32's performance. The ESP32s boasts efficient power usage with deep sleep modes, distinguishing it from the Arduino MKR WiFi 1010, which exhibits higher power consumption, and aligning it closely with the Arduino Nano ESP32 in terms of power efficiency.

The ESP32 chip stands out as a unified solution incorporating both 2.4 GHz Wi-Fi and Bluetooth functionalities, engineered using TSMC's energy-efficient 40 nm technology. Its design prioritizes optimal power management and RF capabilities, ensuring resilience, adaptability, and dependability across diverse usage scenarios and power conditions [12]. The ESP32 emerges as an economical and energy-efficient system-on-chip (SoC) supporting both Wi-Fi and Bluetooth functionalities. Utilizing Tensilica's 32-bit Xtensa LX6 Microprocessor with integrated Wi-Fi and Bluetooth, it succeeds the ESP8266 SoC and is offered in single-core and dual-core variants. Particularly suited for IoT smart energy meter applications, the ESP32 (NodeMCU-32S) depicted in Figure 3 (a) is employed in this study.

Figure 3. (a) NodeMCU ESP32 board (b) Voltage sensor (c) Current sensor (d) OLED (128 x 64)

Distinguished by its enhanced capabilities, the ESP32-S serves as a versatile IoT board, expanding upon the popular ESP8266 line. It notably augments the I/O options, offering flexible functionality along with Bluetooth support. Contrasted with the standard Arduino's AVR processor, it boasts a larger 4 MB Flash memory for program storage and operates at clock speeds of 160 MHz, with the potential for optional overclocking to 240 MHz, thereby ensuring rapid processing. These boards can function autonomously as MCUs, replacing devices like Arduino, or serve as peripherals alongside other MCUs to provide Wi-Fi, Bluetooth, or other unique features. Table 1 provides an overview of some specifications of the ESP32-S development board.

Table 1: Key features of the ESP32-S development board [12]

ESP32-S	Specifications
Microcontroller	Xtensa LX6 32-bit
Clock Speed	160MHz
USB Converter	CP2102
Flash	4 MB
RAM	512Kb
Digital I/O	32 (26 usable)
PWM	16 channels
Analog Outputs	2 channels, 8-bit
Analog Inputs	16 channels, 12-bit
Communications	3 Serial, 4 SPI, 2 I2C, CAN bus, I2S Stereo
Bluetooth	4.2 and BLE (Bluetooth Low Energy)
WiFi	Built-in 802.11 b/g/n 2.4GHz
Buttons	EN (Reset) and IO0 (Boot)
Programming	Compatible with Arduino IDE
Operating Voltage	3.3V internal power and I/O. 5V-9V external power with an on-board regulator

b. Voltage Sensor:

The ZMPT101B module, illustrated in Figure 3 (b), is a compact sensor module for single-phase AC voltage. It relies on a miniature 2mA/2mA precision voltage transformer to perform its measurements. Capable of accurately sensing AC voltage up to 250V (at 50Hz/60Hz), the module incorporates secondary circuitry built around the LM358 dual op-amp chip. This configuration facilitates the regulation of the isolated analog output. With an onboard high-precision amplifier circuit, the module ensures precise signal sampling and appropriate compensation. Moreover, the output voltage's amplitude can be fine-tuned using a potentiometer [13]. Table 2 outlines various specifications of the ZMPT101B module.

Table 2:. ZMPT101B voltage sensor [13]

ZMPT101B AC Voltage Sensor	Specifications
Measure within	250V AC (50Hz/60Hz)
Operating voltage	5V-30V DC
Rated input current	2 mA
Rated output current	2 mA
Isolation voltage	4000V
Output voltage	0-5V
Operating temperature	-40℃~+60℃

c. Current Sensor:

Various types of current sensors are available, including wireless, analog, and digital variants. The selection of a specific type depends on the desired advantages and functionalities required for the application at hand. These sensors will monitor the current values continuously in the appliances or machines within various applications [14]. There are many types of current sensors in the market that could be used for this work. We opt for the Non-Invasive Current Sensor SCT-013 shown in Figure 3 (c). The current transformer SCT-013-030 is capable of being clamped around the supply line of an electrical load to accurately measure the current flow. It functions as an inductor, detecting and reacting to the magnetic field generated by the current-carrying conductor. By analyzing the current produced by the coil, one can determine the amount of current passing through the conductor. For detailed specifications of the current sensor SCT-013-030, please refer to Table 3.

Table 3:. SCT-013-030 current sensor [15]

SCT-013-030 Current Sensor	Specifications
Input current	0-30A
Output type	0-1V
Opening size	13mm*13mm
Dielectric strength(between shell and output)	1000V AC/1min
Operating temperature	-25℃～+70℃

d. OLED (128 x 64) display

The OLED (Organic Light-Emitting Diode) display used in this project is shown in Figure 3(d). The 128x64 display meets the requirements of the project to display instantaneous measured data and energy consumption. The reason is its cheap price, availability, and programmer friendly. Its I2C communication port makes it simple to use. Some specifications of the OLED display are given in Table 4.

Table 4:. OLED display

OLED display	Specifications
Display Size	0.96 inch
Display Driver IC	SSD1315
Resolution	128x64
Port	I2C
Operating Voltage	3.3-5V
Display color	Blue and White

3.3 Software Components

Smart energy meters, which are outfitted with advanced software, provide real-time data on electricity consumption, allowing customers to make informed decisions about their energy consumption patterns. Firstly, the software is critical in collecting and evaluating data from smart energy meters. It enables the smooth integration of numerous sensors and communication protocols, ensuring reliable information measurement and transfer. This data can then be presented using user-friendly interfaces, allowing users to analyze their energy usage habits and highlight areas for improvement in efficiency.

Moreover, the software supports remote monitoring and control. Users can access their meter data via mobile applications or web portals, providing them with real-time insights into their energy consumption even while they are away from home. This feature raises consumer knowledge of their electricity usage habits and encourages them to adopt more sustainable behaviors.

Furthermore, the software facilitates demand response programs by allowing utilities to remotely modify power supply based on peak demand periods. Utilities may enhance grid operations and reduce pressure during peak demand periods by combining smart meters with cognitive algorithms. This not only improves grid resilience but also helps to reduce carbon emissions by minimizing the need for new electricity generation.

The software components of the project are crucial for the successful implementation of the Smart Energy Meter. There are two main parts: one implemented on the ESP32s microcontroller and the other utilizing the ThingSpeak web server. The programming of the ESP32s board is done using the Arduino Integrated Development Environment (IDE) software, which employs a language similar to C++. The ESP32s is programmed to perform the following tasks:

- Read AC Voltages and Currents: The ESP32s interfaces with the three voltage sensors (ZMPT101B) and three current sensors (SCT-013-030) to acquire real-time AC voltage and current measurements from the three phases. These sensor readings are essential for accurate energy consumption calculations.
- Process and Calculate Energy Consumption: The microcontroller processes the received voltage and current data to calculate the energy consumption for each phase. Utilizing mathematical formulas and power calculations, the ESP32s derives real-time power consumption for efficient energy monitoring.
- Display Data on OLED: The calculated energy consumption values are displayed on the OLED display (128 x 64). This provides users with immediate access to relevant data, allowing them to make informed decisions regarding their energy usage.
- Send Data to ThingSpeak: The ESP32s is configured to send the measured and calculated data to the ThingSpeak web server. This cloud integration allows for secure storage and management of energy consumption data. ThingSpeak provides users with the ability to access and visualize real-time data from their devices, fostering better energy management practices.

The ThingSpeak web server acts as the other major software component, offering the following functionalities:

- Internet Connectivity: ThingSpeak facilitates the connection of devices, including the Smart Energy Meter, to the Internet. This enables seamless data transfer and remote monitoring capabilities.
- Real-Time Data Visualization: Users can create real-time data visualizations, including graphs and charts, to display the energy consumption patterns of the three phases. These visualizations enhance user understanding and awareness of their energy usage.

By integrating these software components effectively, the Smart Energy Meter becomes a powerful tool for users to monitor and manage their energy consumption across multiple phases in real time. The combination of ESP32s programming and ThingSpeak cloud services enables users to make informed decisions for energy efficiency and sustainable energy practices.

4. The Smart Energy Meter Prototype

To accurately measure and track energy use, an energy meter system's architecture is essential. Sensors, microcontrollers, and display units are just a few of the parts that make up this system. The sensors are in charge of measuring the quantity of energy used by various appliances and devices. The microcontroller processes these readings and computes and records the overall energy consumption in memory. The display device gives users access to this information in an intuitive way.

Accuracy and dependability must be guaranteed in the system's design. Consequently, reliable sensors with low error rates are crucial. The microcontroller should also be able to do complex computations rapidly and effectively to prevent measurement inaccuracies.

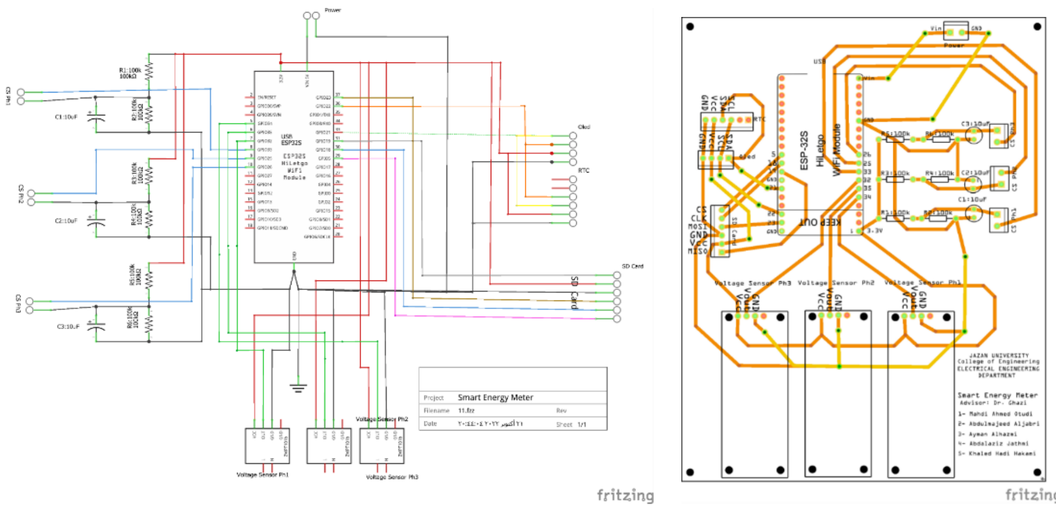
Additionally, the design should take into account things like power efficiency and ease of installation. To reduce avoidable waste, energy metering devices should use as little electricity as possible themselves. Additionally, they ought to be created so that installation is simple and doesn't call for any additional wiring or substantial alterations. Figure 4 (a) presents the connection diagram of the three-phase energy meter IoT board. The system incorporates an ESP32s microcontroller, three voltage sensors (ZMPT101B), three current sensors (SCT-013-030), an OLED display (128 x 64), six 100kΩ resistors, and three 10uF capacitors. This integrated setup allows for accurate measurement and monitoring of energy consumption in three phases. The voltage sensors for phase#1, phase#2, and phase#3 are connected to the analog inputs GPIO34, GPIO35, and GPIO32, respectively. These voltage sensors provide real-time measurements of the respective phase voltages, contributing to the overall energy consumption analysis.

Similarly, the current sensors for phase#1, phase#2, and phase#3 are connected to the analog inputs GPIO33, GPIO25, and GPIO26, respectively. These current sensors enable the accurate measurement of the currents flowing through each phase, essential for calculating the power consumption accurately.

To facilitate communication with the OLED display, the ESP32s uses the I2C communication protocol. The OLED display is connected to the ESP32s through SDA pin#33 and SCL pin#36. This connection enables the display of real-time energy consumption data on the OLED screen, providing immediate feedback to the user. Figure 4 (b) showcases the two-layer Printed Circuit Board (PCB) design of the IoT board, ensuring the components are securely integrated for robust operation. The PCB design enables efficient and compact placement of components, optimizing the overall system's footprint. In the upcoming version of the system, the Real Time Clock (RTC) and the SD card connectors will be incorporated to enhance data storage capabilities. These additions will enable the system to record energy consumption data over time, providing valuable insights into energy usage patterns and trends.

Overall, the developed IoT board represents an advanced and comprehensive solution for collecting customers' home energy consumption data in three phases. Its accurate measurements, real-time data display, and future expansions make it an ideal tool for promoting energy efficiency and supporting smart grid monitoring applications.

Figure 5 illustrates the experimental setup of the Smart Energy Meter, where a curling iron is used as the load. The prototype's performance is evaluated through a series of experiments conducted on phase#1 of the power distribution network. During the experiments, real-time data from the curling iron's power consumption is displayed on the OLED display, providing immediate feedback to the user. The Smart Energy Meter's capability to monitor and measure power consumption is not limited to phase#1 only. The experimentation is extended to include phase#2 and phase#3 of the power distribution network as well. By conducting the same experiments on all three phases, the prototype's efficiency and accuracy across the entire electrical system are evaluated. The experimental results from all three phases, phase#1, phase#2, and phase#3, are not only displayed on the OLED screen but are also transmitted to an IoT cloud server. This cloud integration ensures that the data is securely stored and easily accessible from any internet-enabled device. The use of an IoT cloud server facilitates remote monitoring and analysis of the power consumption patterns, enabling users to make informed decisions regarding energy usage and management. The experimental setup and subsequent data collection and transmission demonstrate the prototype's successful implementation and its ability to monitor power consumption in real time across different phases of the power distribution network. These results validate the Smart Energy Meter's potential to contribute significantly to efficient energy utilization and promote smart home technologies.



(a) (b)

Figure 4.. Design of energy meter system (a) Circuit diagram (b) Printed Circuit Board

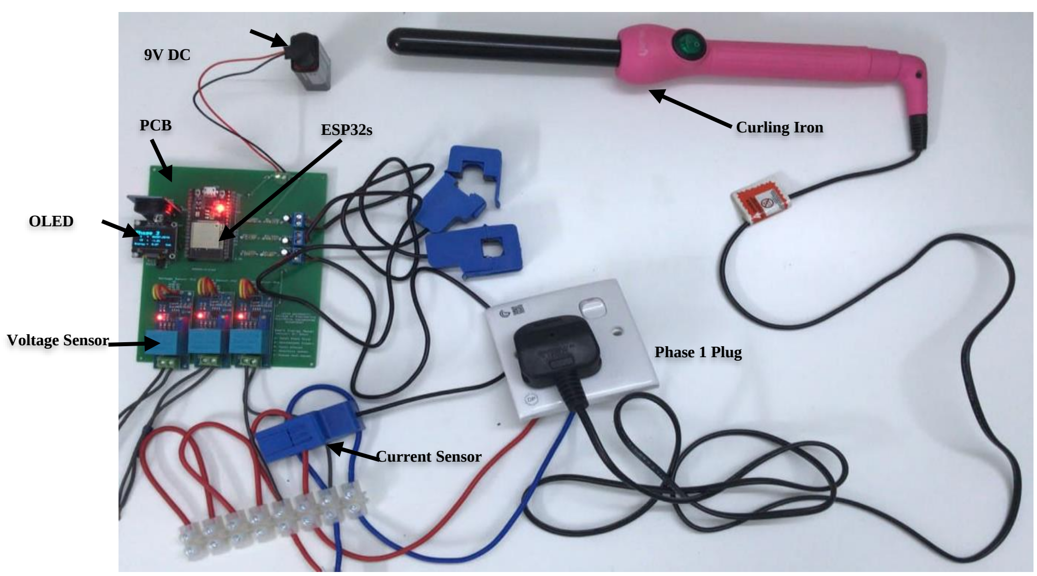
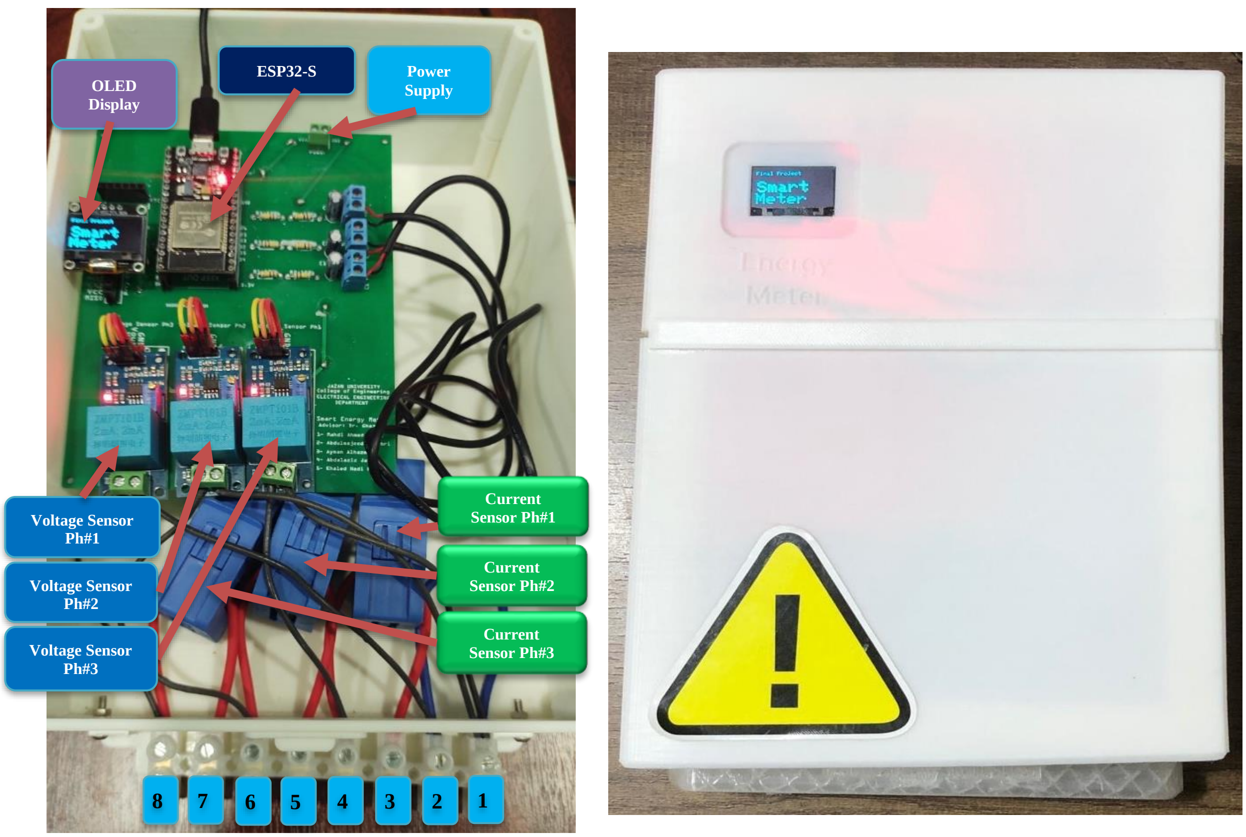


Figure 5.. Curling iron plugged in the Smart Energy Meter

Figure 6 (a) shows the fully assembled prototype of the proposed smart energy meter, which has been thoroughly tested and calibrated for accurate measurements. The prototype is equipped with the necessary sensors and components to measure current and voltage from three-phase loads effectively. The system has been carefully integrated into a printed circuit board (PCB) to ensure optimal performance and reliability.

In Figure 6 (b), the box designed using Fusion 360 software provides a secure and user-friendly enclosure for the assembled prototype. The bottom side of the box features connectors specifically designed for easy and safe attachment of three-phase loads. The 8-port connector arrangement on the bottom side of the box, from right to left, includes (1) neutral input, (2) neutral output, (3) line#1 input, (4) line#1 output, (5) line#2 input, (6) line#2 output, (7) line#3 input, and (8) line#3 output. This configuration ensures straightforward and risk-free connections with the Non-Invasive Current Sensor SCT-013. The front cover of the box hosts an OLED screen, which acts as a user interface to display real-time energy consumption data. This display provides users with instant access to crucial energy consumption information, promoting awareness and informed energy management decisions. Once the system is in operation, the box is securely closed, safeguarding users from accidental contact with any internal components and eliminating the risk of electric shock. The careful design and integration of the prototype and the protective box emphasize user safety, convenience, and efficient energy monitoring. The smart energy meter, with its secure enclosure, advanced measurements, and real-time data display, holds great potential to contribute to smart grid technologies and sustainable energy management practices.



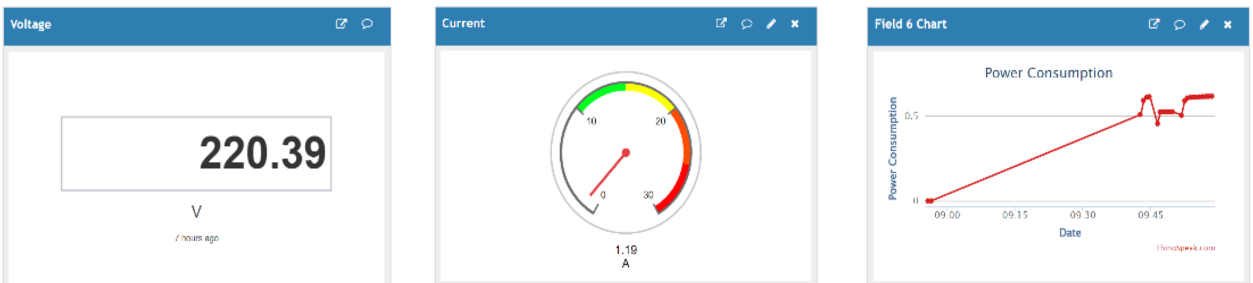
(a) (b)

Figure 6:. (a) The final prototype of the Smart Energy Meter (b) The box

The smart energy meter successfully measured the current and voltage using different sensors, enabling accurate evaluation of power consumption. One of the key features of the proposed system is its seamless transmission of real-time data to the cloud server, eliminating the need for local data storage. The measured currents, voltages, and computed power are promptly sent to the Thingspeak web server for remote monitoring and analysis. As shown in Figure 7 (a), the real-time measurements of voltage exhibited stable trends, reflecting the consistent energy supply. Figure 7 (b) displayed concurrent readings of current, providing insights into the dynamic power consumption patterns. The calculated power consumption, as depicted in Figure 7 (c), demonstrated the system's ability to process data accurately.

By leveraging the Thingspeak web server, users can conveniently access and visualize the data from any internet-enabled device. This feature enhances the system's usability and facilitates prompt decision-making regarding energy management strategies. The absence of local data storage minimizes the risk of data loss and reduces the hardware complexity of the smart energy meter.

In conclusion, the results demonstrate the efficacy of the smart energy meter in real-time measurement, data transmission, and remote monitoring through the integration with the Thingspeak web server. The system's ability to capture voltage, current, and power consumption data provides valuable insights for efficient energy utilization and supports sustainable practices in power distribution.



(a) (b) (c)

Figure 7:. (a) Measured voltage (b) Measured current (c) Power consumption

5. Conclusions

In conclusion, how we manage our energy resources has changed as a result of the development and deployment of a smart energy meter system using the Internet of Things. It offers real-time monitoring, analysis, and control capabilities that enable utility companies to efficiently optimize their operations while empowering consumers to make knowledgeable decisions about their energy usage. This technology is unquestionably a game-changer in the area of energy management due to its many advantages, including improved efficiency, lower prices, and environmental sustainability.

In this paper, we presented a comprehensive study on the development and implementation of a Smart Energy Meter with cloud connectivity, designed to monitor and analyze real-time energy consumption. The system was built to measure current and voltage, calculate energy consumption, and seamlessly send the data to the cloud-based web server, ThingSpeak. In conclusion, the Smart Energy Meter presented in this paper represents a significant advancement in the field of energy monitoring. By harnessing the power of cloud connectivity, it offers a convenient and efficient solution for real-time energy consumption monitoring.

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