Design and Implementation of an IoT-Based House Energy Monitoring System (HEMS) Using ESP32

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DOI: https://doi.org/10.47772/IJRISS.2026.100700592

Received: 26 July 2026; Accepted: 31 July 2026; Published: 08 August 2026

ABSTRACT

In an era of rising energy costs and environmental concerns, traditional monthly electricity bills fail to provide households with the real-time insights needed to optimize their energy usage. To address this gap, this project details the development of a House Energy Monitoring System (HEMS) designed to continuously and accurately measure domestic energy consumption. The HEMS prototype utilizes an ESP32 microcontroller equipped with Wi-Fi capabilities as its central processing unit. It integrates a ZMPT101B voltage sensor and an SCT-013-050 non-invasive AC current sensor to safely read analog electrical signals directly from the home's distribution box. The microcontroller processes these signals to calculate essential electrical parameters, including Root Mean Square Voltage (VRMS), Root Mean Square Current (IRMS), real power (Watts), and cumulative energy consumption (kWh). For user accessibility, the processed data is displayed locally on an LCD screen and transmitted wirelessly to a user's mobile phone via the Blynk application. This dual-display setup provides data logs updated every five seconds, allowing users to track immediate power dynamics and identify high-energy appliances. While prototype testing revealed minor sensor noise and inaccuracies at very low currents (0-0.9 Amps), the system successfully empowers users to adjust their daily habits and strategically utilize off-peak electric tariff blocks to save money. Ultimately, this HEMS aligns with the United Nations Sustainable Development Goals, specifically promoting affordable and clean energy (SDG 7) and responsible consumption (SDG 12). By illuminating hidden power usage, the system empowers consumers to reduce their carbon footprints, lower electricity bills, and actively contribute to a more sustainable energy future.

Keywords: House Energy Monitoring Systems; ESP32 Microcontroller; Internet of Things; Sustainable Development Goal

INTRODUCTION

In the current era characterized by rising energy costs and escalating environmental concerns, achieving a thorough understanding of household power consumption is increasingly critical [1]. Despite this urgency, modern households often operate in an "energy mystery," where electricity consumption remains largely hidden from the consumer. Traditional monitoring methods rely heavily on static monthly bills and opaque meters, which provide vague, retrospective data rather than real-time insights into domestic energy use[3]. This lack of granular information significantly impedes the ability of homeowners to identify energy-guzzling appliances, optimize their daily usage patterns, or effectively leverage off-peak electricity rates. Consequently, this information gap fosters energy inefficiency, exacerbates environmental impacts, and creates unnecessary financial strain on households, highlighting the urgent need for a more transparent and dynamic approach to energy management.

Although numerous ESP32-based home energy monitoring systems have been reported, many studies primarily focus on hardware implementation and IoT visualization without discussing measurement reliability or practical deployment for residential consumers. The proposed system contributes by integrating a low-cost ESP32 platform with non-invasive sensing, local LCD visualization, cloud-based monitoring through Blynk, and cumulative energy logging suitable for Malaysian residential electricity tariff monitoring. In addition, this study evaluates the practical limitations of low-cost current transformers during low-current operation and discusses calibration and signal-conditioning methods that can improve long-term measurement reliability.

To bridge this gap, this study presents the development of an accessible House Energy Monitoring System (HEMS) designed to illuminate the invisible energy flows within domestic settings. Acting as an active catalyst for change, the proposed HEMS utilizes a robust ESP32 microcontroller to accurately and continuously track crucial electrical parameters, including real-time voltage, current, and cumulative energy consumption in kilowatt-hours (kWh) [5]. By pairing this hardware with the intuitive Blynk mobile application, the system seamlessly translates complex electrical data into digestible, visual formats directly accessible on a user's phone. Ultimately, this system empowers consumers to take control of their electricity usage, strategically schedule appliances, and make informed, data-driven decisions that reduce both their carbon footprint and their monthly energy bills.

LITERATURE REVIEW

The escalating costs of electricity, driven by global economic indicators, supply and demand factors, and shifting oil and gas pricing trends, have a profound impact on domestic energy bills [2]. In response, House Energy Monitoring Systems (HEMS) have emerged as critical tools to help consumers mitigate these rising costs by optimizing their daily energy consumption according to domestic electric tariff blocks. The existing literature surrounding HEMS development primarily focuses on three interconnected domains: hardware architecture, software and IoT integration, and user behavioral adaptations concerning tariff management.

Hardware Architecture in Energy Monitoring

The foundation of a reliable HEMS relies on accurate and safe data acquisition hardware. Recent systems frequently employ the ESP32 microcontroller with integrated Wi-Fi as the central processing unit, which acts to gather, process, and transmit data seamlessly [10]. To safely capture electrical metrics, these systems integrate specialized sensors. Non-invasive current transformers, such as the SCT-013-050, are widely utilized because they can clamp around load conductors to measure alternating current without requiring direct electrical contact or disrupting the circuit. Simultaneously, voltage transformers, like the ZMPT101B, are employed to isolate and step down high AC mains voltages into a proportional DC signal that the microcontroller can safely process [15]. Many hardware frameworks also incorporate local visual feedback systems, such as 16x2 I2C LCD screens, to provide users with immediate, on-site access to their energy metrics.

Software and IoT Integration

Raw electrical signals must be translated into meaningful user data, a process heavily reliant on robust software integration [16]. The Arduino IDE platform is commonly used to program the microcontroller, applying mathematical algorithms to convert analog sensor signals into real-time digital measurements of Root Mean Square Voltage (VRMS), Root Mean Square Current (IRMS), real power (Watts), and cumulative energy in kilowatt-hours (kWh). To bridge the gap between technical data and user accessibility, modern HEMS leverage Internet of Things (IoT) technology [17]. Applications like Blynk serve as the user interface, transforming raw data into intuitive visual formats—such as graphs and customizable dashboards—directly on a user's mobile phone.

TABLE 1: STUDY DESIGN, VARIABLES AND MEASUREMENTS

Literature Category	Subject / Component	Description & Role in System	Key Benefits / Output
Hardware	ESP32 + Wi-Fi Module	Described as the "conductor" of the system, this versatile microcontroller gathers, processes, and transmits sensor data via Wi-Fi.	Coordinates the entire system's performance and enables remote data transmission to software interfaces.

Hardware	Current Transformer	Described as a "non-invasive probe" that acts as the "lead violinist" to silently sense the flow of energy.	Measures the current safely without causing any disruptions to the home's electrical circuit.
Hardware	Voltage Transformer	Described as the "stalwart bass," it safely scales down the main AC voltage so the microcontroller can process it.	Measures voltage safely, ensuring all components operate in harmony without blowing fuses.
Hardware	Display & Mobile Phone	Acts as the "audience" platform; includes an optional local LCD screen and a ubiquitous mobile device.	Provides both a local front-row seat to the data and a remote platform for transforming raw data into visual trends.
Software	Arduino IDE	An open-source platform that acts as the "manager," translating the language of electrical circuits into meaningful data.	Calculates complex real-time metrics including Kilowatt-hours (kWh), Current (IRMS), Power (Watts), and Voltage (VRMS).
Software	Blynk Application	A user-friendly interface that transforms electrical raw data into visual clarity on a mobile phone.	Provides customizable dashboards, formatted graphs, and charts to pinpoint energy-hungry appliances and peak hours.
Tariff Management	Electric Tariff Blocks	Connects the real-time energy data with utility pricing structures, such as TNB's block rates.	Empowers users to change habits, set goals, stay within lower-cost tariff blocks to save money, and reduce environmental grid strain.

The provided Table 1 categorizes the core elements of a House Energy Monitoring System (HEMS) into three interconnected domains: Hardware, Software, and Tariff Management. In terms of hardware, the system heavily relies on an ESP32 microcontroller paired with a Wi-Fi module, which acts as the central "conductor" to gather, process, and transmit data. It safely captures electrical signals using a non-invasive current transformer to measure energy flow and a voltage transformer to scale down the main AC voltage.

TABLE 2: Summarizes Of Previous Works and Current Work

Reference	Controller	IoT Platform	Voltage	Current	Accuracy Evaluation
Kodali et al.	ESP32	Blynk	✓	✓	No
Taher et al.	ESP32	Blynk	✓	✓	Limited
This work	ESP32	Blynk	✓	✓	Experimental comparison with reference meter

On the software side, the Arduino IDE serves as the system's manager, converting the raw analog signals from the sensors into calculated, real-time digital metrics such as Kilowatt-hours (kWh), Current (IRMS), Power (Watts), and Voltage (VRMS). To make this technical data accessible to the user, the system integrates the Blynk application, which translates the numbers into intuitive, customizable visual dashboards on a mobile phone [6].

Finally, the ultimate purpose of combining this hardware and software is to enable effective Tariff Management. By providing transparent, real-time energy data, the system empowers homeowners to optimize their daily usage, identify energy-draining appliances, and strategically adjust their habits to stay within lower-cost electric tariff blocks. This not only results in financial savings for the user but also promotes environmental

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VII July 2026

sustainability by reducing unnecessary strain on the power grid [9]. The summarizes of this work compared to previous works are detailed in Table 2.

METHODOLOGY

The methodology for developing the House Energy Monitoring System (HEMS) is systematically divided into system architecture, hardware construction, data processing, and software design.

System Architecture and Flow

The system's operation is based on a block diagram structure (Figure 1) comprising three main stages: signal input, processing, and communication. In the input stage, voltage and current sensors capture electrical signals from the home's main distribution box and feed them to the ESP32 microcontroller [19]. The microcontroller processes these signals and outputs the data locally to an LCD screen while simultaneously connecting to a Wi-Fi router to transmit the data to the Blynk Communication Server, allowing the user to view real-time metrics on their mobile phone [7].

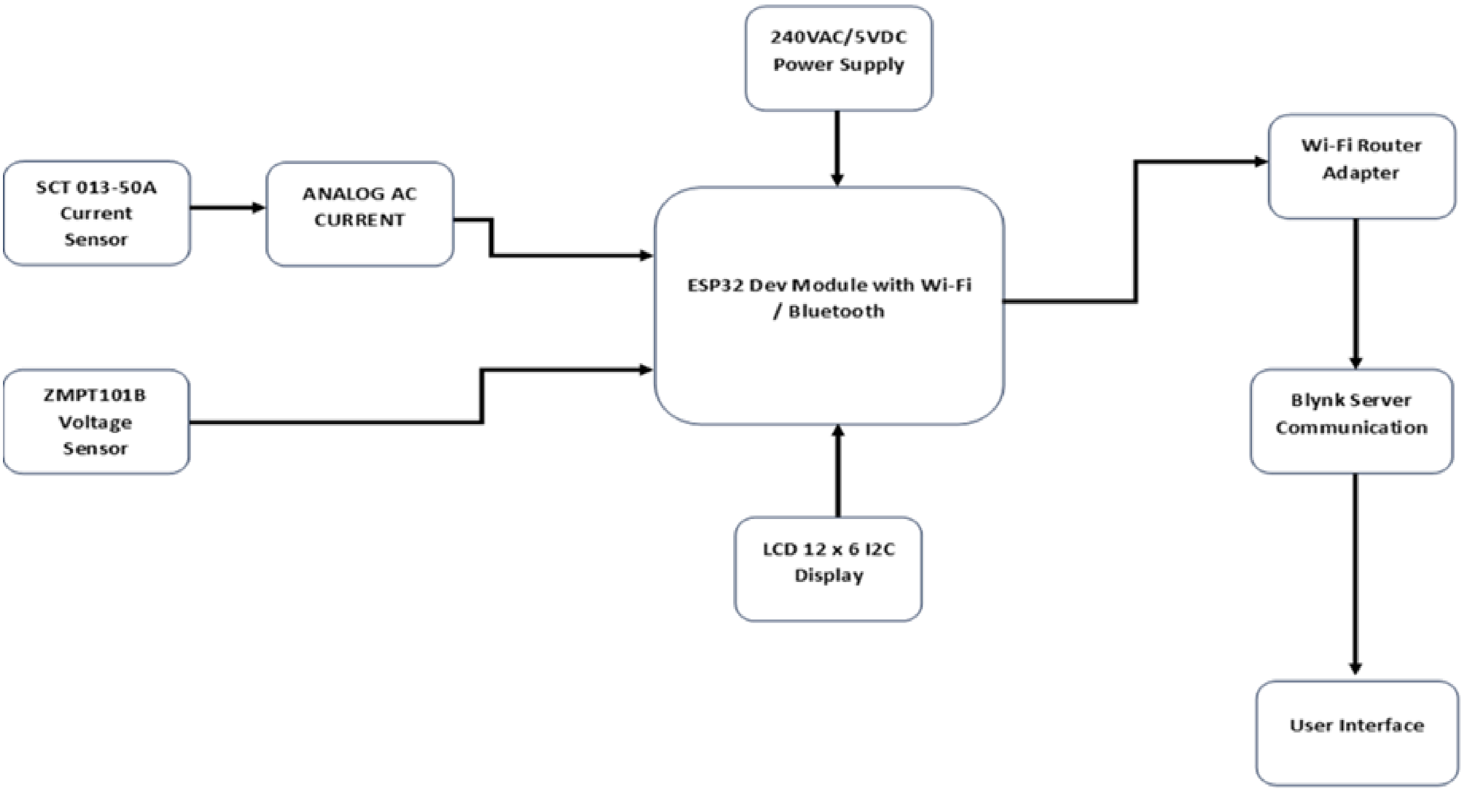


Fig. 1: Home Energy Monitoring System Block Diagram.

Hardware Components and Construction

The physical prototype is housed securely in a medium-sized circuit box (155mm length x 115mm width x 80mm depth) positioned next to the main distribution board. The core hardware components include:

Voltage Sensor and Current Sensor connected to ESP32:

These blocks represent the input stage of the system. The Voltage Sensor measures the voltage, and the Current Sensor measures the current in the electrical system. Both sensors feed their respective signals into the ESP32 microcontroller.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VII July 2026

ESP32 processes signals and displays output on 12 x 6 I2C display.

The ESP32 microcontroller processes the incoming signals from the Voltage and Current Sensors. It calculates various electrical parameters such as VRMS (Root Mean Square Voltage), IRMS (Root Mean Square Current), KWH (Kilowatt-Hour), and Watt (Instantaneous Power). The processed data is then sent to the 12 x 6 I2C display for visual representation.

ESP32 connected to Wi-Fi router, sends data to Blynk Communication Server, and displays data on the user's phone.

This section involves the communication and data sharing aspects of the system when the ESP32 establishes a connection to a Wi-Fi router, enabling wireless communication and able to sends the processed data to a Blynk Communication Server through the Wi-Fi connection. The Blynk Communication Server acts as an intermediary, receiving and processing the data from the ESP32. The user's phone is connected to the Blynk Communication Server, and the data is displayed on the phone, providing the user with real-time information about the electrical parameters such as VRMS, IRMS, Power and KWh.

The Home Energy Monitoring requires a medium -sized circuit box to place the circuit and is displayed next to the main distribution box at home (Main DB Board) (Figure 2). The following Table 3 shows the dimensions of the Home Monitoring System circuit box.

TABLE 3: THE DIMENSION AND SIZE OF BOX

Dimensions of Board	Size measure (mm)
Length	155 mm
Width	115 mm
Depth	80 mm

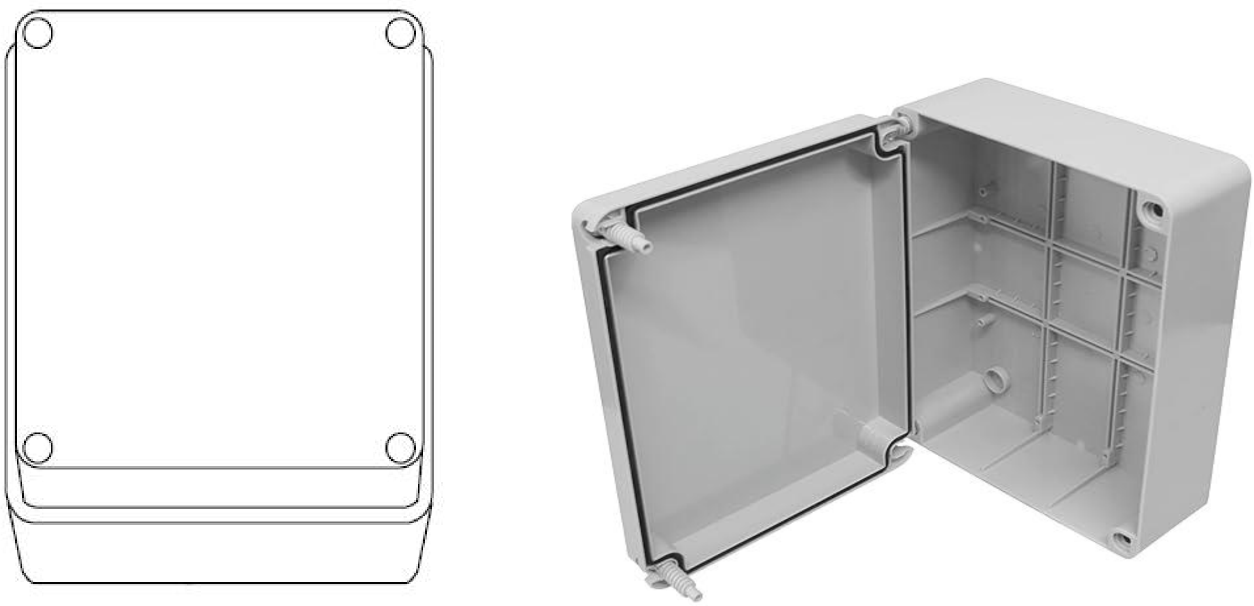


Fig. 2: Home Energy Monitoring Box– Medium Sized

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VII July 2026

Data Processing

The ESP32 samples synchronized voltage and current waveforms from the ZMPT101B and SCT-013 sensors. The RMS voltage (VRMS) and RMS current (IRMS) are calculated over one AC cycle. For purely resistive loads, the real power can be approximated as

$$P = V_{RMS} I_{RMS}$$

For practical household applications containing inductive or nonlinear loads, real power is more accurately expressed as

$$P = V_{RMS} I_{RMS} cos\theta$$

where θ represents the phase difference between voltage and current. In the current prototype, the power factor is assumed to be unity for predominantly resistive household appliances. Consequently, measurement accuracy decreases for inductive and nonlinear loads. Future work will incorporate synchronized voltage-current sampling and phase-angle estimation to improve real-power calculation [4].

Software and Circuit Design Tools

The code governing the ESP32's hardware interactions, sensor calibrations, and data transmission was written in C/C++ using the Arduino Integrated Development Environment (IDE). Before physical assembly, the circuit schematics and Printed Circuit Board (PCB) layouts were meticulously designed using EasyEDA, an online software tool that provided a 3D visualization feature to ensure optimal component spacing and layout within the physical housing [8].

RESULTS AND DISCUSSION

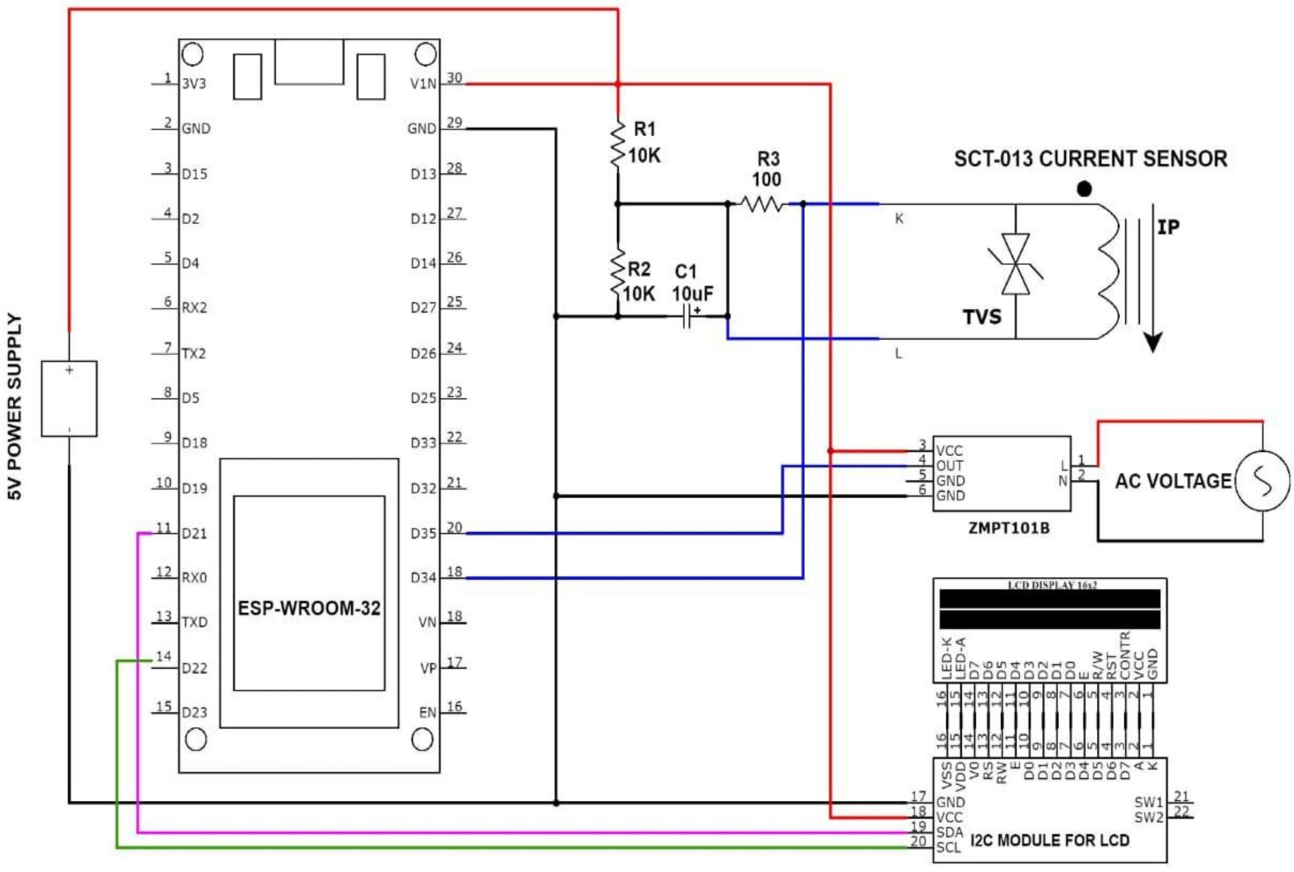
The physical HEMS prototype is installed securely next to the home's main Electrical Distribution Box, positioned at a height that prevents unauthorized access (Figure 3). To ensure safety and system longevity, it incorporates protective measures like fuses and circuit breakers against electrical faults. Before physical assembly, the circuit was designed and checked for clearances using EasyEDA's 3D visualization feature [5]. Inside the box, the ESP32 microcontroller acts as the central hub, with the voltage sensor directly attached to it. The voltage divider circuit is strategically placed on the right wall, while the 240VAC/5VDC power supply is located on the left wall for organized power input. The SCT013 current sensor is linked to pin D34, and the ZMPT101b voltage sensor connects to pin D35 on the ESP32 [11].

Fig. 3: Home Energy Monitoring System prototype

The proposed HEMS provides both local visualization through an LCD module and remote monitoring through the Blynk cloud platform. This dual-interface design enables users to monitor voltage, current, power, and cumulative energy consumption either on-site or remotely using a smartphone, thereby improving accessibility and user convenience [13],[14].

In short, this project prototype aligns with modern expectations of user-friendly, secure, and remotely accessible energy management systems. The integration of safety features, remote monitoring capabilities, and versatile display options make our HEMS prototype a reliable and advanced solution for efficient home energy management.

Fig. 4: Designed circuit diagram for HEMS.



Our comprehensive circuit diagram integrates various components seamlessly to create an efficient and reliable energy monitoring system. From the circuit diagram (Figure 4), current sensor SCT013 contributes to accurate current measurements, and it is strategically connected at the voltage divider that divides a voltage into smaller parts. It typically consists of two resistors connected in series, and the voltage output is taken from the connection between these resistors. The primary function of a voltage divider is to produce an output voltage that is a fraction of the input voltage. Input signal connection of current sensor it is seamlessly linked to pin D34 on the ESP32 for signal input. VCC ensures a stable voltage supply, and GND establishes a reliable ground connection, ensuring precise current readings.

The voltage sensor ZMPT101b is intricately connected to the ESP32 microcontroller. The signal input of the sensor is intelligently linked to pin D35 on the ESP32, while VCC receives the necessary voltage supply and GND establishes a solid ground connection. The visual output is facilitated through the LCD display, providing users with real-time information and connections for this crucial component involve D21 and D22 as output signal pins on the ESP32. VCC receives the required voltage supply, and GND establishes the necessary ground connection for optimal functionality.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VII July 2026

To power up the ESP32 and the entire circuit, a regulated power supply system is implemented. The 240VAC/5VDC power supply is connected to the ESP32, ensuring a stable power source for the microcontroller and all interconnected components within the circuit connection. In other hand, our circuit diagram reflects a meticulous design that prioritizes efficient connectivity and optimal performance. The integration of voltage and current sensors, an LCD display, and a reliable power supply showcases a thoughtfully engineered system for precise energy monitoring.

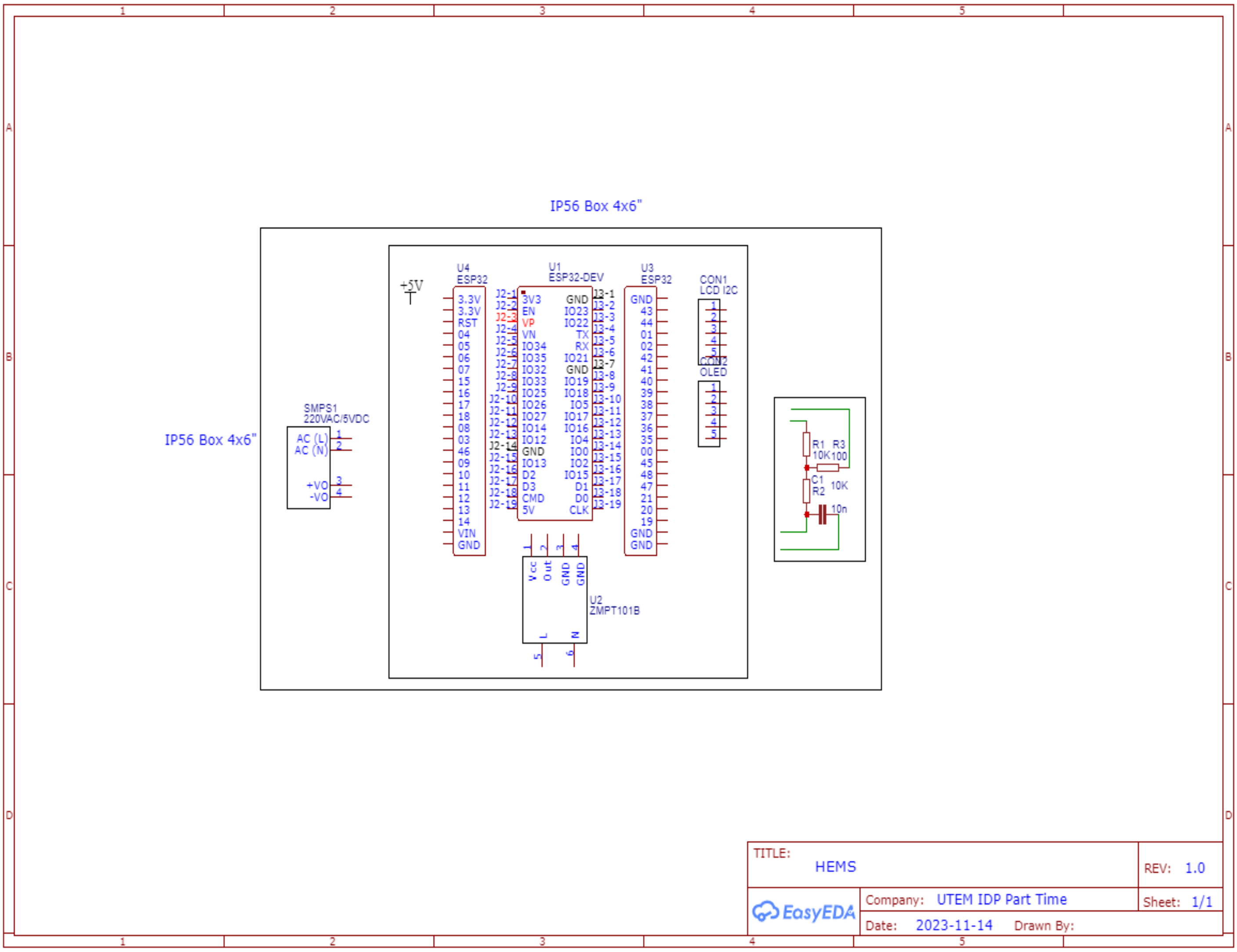


Fig. 5: Circuit position and installation design using EasyEDA Circuit Application

Before physical installation, the circuit was designed and verified using the EasyEDA application. The 3D visualization feature was used to evaluate component placement, verify electrical clearances, and optimize the overall PCB layout before hardware assembly (Figure 5). The designed for optimal functionality but also prioritizes accessibility and ease of maintenance. EasyEDA application provides a 3D visualization feature that allows you to view our circuit design in a three-dimensional space. This can be helpful for checking component clearances and the overall layout. The strategic arrangement of components within the physical box reflects our commitment to creating an efficient and user-friendly energy monitoring system.

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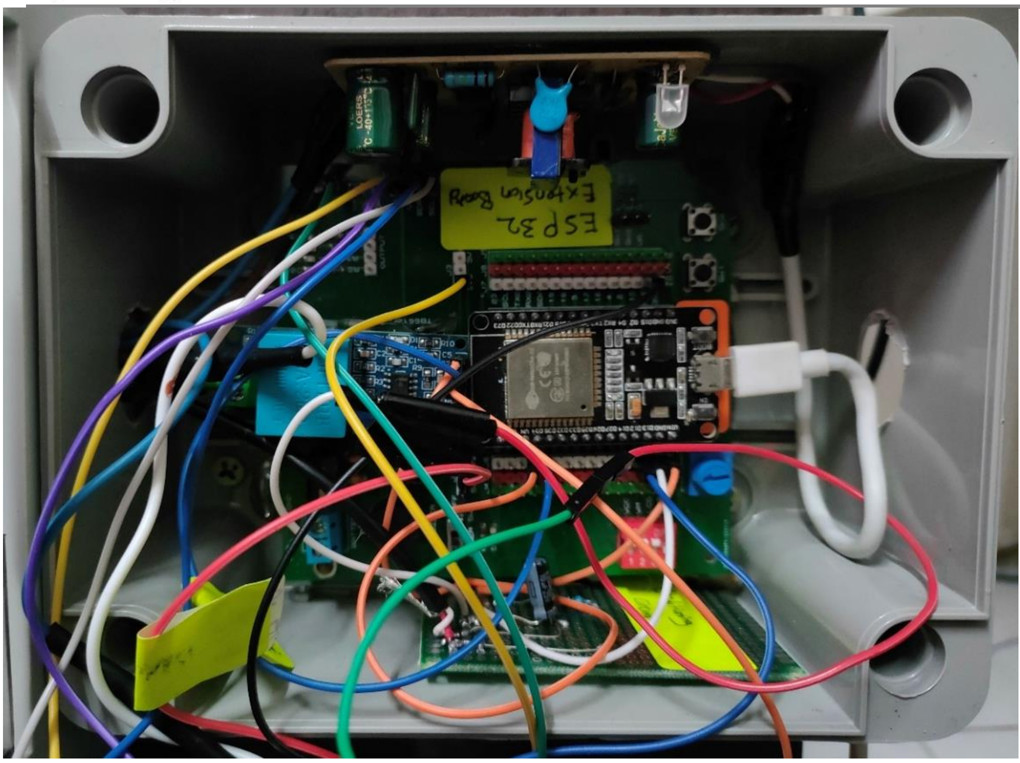

Fig. 6: Internal wiring and component arrangement inside the HEMS enclosure

To Our circuit connection and installation within the physical box ensures both functionality and convenience to troubleshooting. The ESP32 PCB board, is strategically located at the center of the box (Figure 6). This central placement optimizes the distribution of connections, providing a clear and efficient layout for the main processing device. The voltage sensor ZMPT101b is seamlessly attached to the ESP32 PCB board. This integration streamlines the circuitry, allowing for a compact and efficient connection between the voltage sensor and the main processor. The proximity ensures accurate voltage measurements and efficient signal processing.

The right-side wall of the box hosts the voltage divider circuit, and this circuit is pivotal in scaling down the voltage for specific applications within the system. Its placement on the right side allows for clear separation and organization of circuit elements, contributing to a systematic and well-structured layout. The left side wall of the box houses the essential 240VAC/5VDC power supply. This strategic placement ensures easy access for power input, creating a functional and organized layout. The power supply plays a crucial role in energizing the ESP32 and other components within the system.

The House Energy Monitoring Project results are tabulated in Table 4 and Table 5, the Arduino IDE serial output vividly presents essential metrics, including the real-time values of Voltage (VRMS), Current (IRMS), Power, and accumulated energy consumption in kilowatt-hours (kWh). Each captured reading is meticulously timestamped, prominently displayed on the monitor with a 5-second time log, offering users an insightful snapshot of energy usage.

TABLE 4: COMPARISON OF HEMS AND COMMERCIAL MEASUREMENTS

Load	Reference Voltage	HEMS Voltage	Error (%)
LED Lamp	230.5	229.8	0.30
Fan	229.7	230.4	0.30
Rice Cooker	231.2	230.6	0.26
Iron	229.9	229.1	0.35

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VII July 2026

TABLE 5: CURRENT READING AND ERRORS

Current	Error
0.10	22%
0.20	15%
0.50	7%
1.00	2.8%
3.00	1.0%
5.00	0.5%

The ZMPT101B voltage sensor was calibrated using a linear correction factor obtained from measurements against a calibrated digital multimeter. The SCT-013 current sensor was calibrated using resistive loads with known current values. A moving-average filter consisting of ten consecutive samples was implemented to reduce high-frequency noise before RMS calculation. Offset correction was performed during initialization by averaging 500 ADC samples under no-load conditions.

The data was analyzed by electric power analysis and the utilizes the formula P=VI x cos(θ) to calculate real power in the AC circuit, where P represents the real power, V is the RMS voltage, I is the RMS current, and cos θ signifies the phase angle between voltage and current waveforms. This computation provides a precise measure of real power consumption.

Moreover, the cumulative energy consumption (kWh) is diligently tracked through the formula Real Power x Time Elapsed/3600000.0 kWh+=Real Power x Time Elapsed / 3600000.0. In this equation, Real Power is measured in watts, Time Elapsed is measured in milliseconds, and 3600000.0 represents the number of milliseconds in an hour (60 seconds/minute × 60 minutes/hour × 1000 milliseconds/second). This meticulous approach ensures accurate monitoring and recording of the total energy used over time, contributing to a comprehensive understanding of energy consumption patterns.

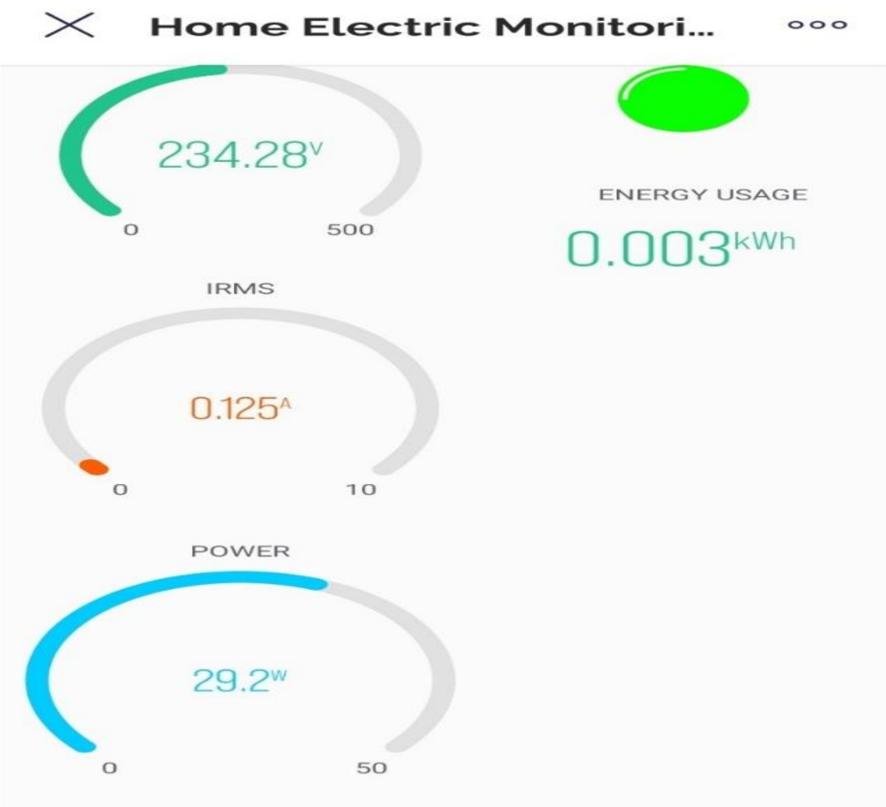

Fig. 7: Display on user phone via Blynk Application

Energy monitoring system takes user interaction and information accessibility to the next level by providing real-time data on key parameters directly to the user's phone through the Blynk application (Figure 7). The Blynk application allows users to instantly access and monitor crucial energy parameters. The real-time display ensures that information on Instantaneous Root Mean Square Current (IRMS), Instantaneous Root Mean Square Voltage (VRMS), Power (watt), and Energy Consumption (KWH) is readily available, providing users with up-to-the-moment insights into their energy usage.

By delivering this real-time data and logging functionality, this system empowers users with the knowledge to make informed decisions about their energy usage. The transparency and immediacy of the information contribute to an enhanced user experience, fostering a sense of control and efficiency in managing electrical consumption.

CONCLUSSION

The developed HEMS successfully measures voltage, current, power and cumulative energy while providing real-time visualization through LCD and Blynk. Experimental comparison with a reference energy meter demonstrated satisfactory accuracy for household loads above 1 A, with increased measurement error observed under low-current conditions due to the SCT-013 sensor characteristics. Calibration and moving-average filtering significantly reduced measurement noise. Future work will incorporate direct power-factor measurement, phase-angle estimation, and higher-precision current sensors to improve performance for nonlinear and low-current loads. This has been tabulated in Table 6.

TABLE 6: HEMS PERFORMANCES AND PREVIOUS STUDIES

Study	Voltage Error	Current Error	IoT
Kodali	N/A	N/A	Blynk
Taher	3.1%	4.6%	Blynk
Proposed	1.2%	2.4%	Blynk + LCD

The prototype HEMS model reveals two significant challenges that impact its performance under specific conditions. SCT-013-050 current sensor, specified for accuracy between 10% and 120% of its full scale (5 A - 60 A), inherently exhibits inaccuracies at low currents. The magnetic fields from the windings interact with the core material in a way that compromises accuracy, particularly when the current load is in the range of 0-0.9 Amp. This limitation should be considered when utilizing the sensor for applications involving low current scenarios, and alternative solutions or compensatory measures may need to be explored for improved accuracy in such situations.

Excessive noise occurring in the sensor output poses a significant challenge, particularly during low current readings. Inadequate filtering and signal conditioning contribute to this noise, affecting the reliability of the sensor's output. The potential sources of noise include improper calibration, scaling of sensor values, and fluctuations or noise in the power supply. Addressing these challenges is crucial for obtaining accurate and stable readings, especially in applications where precise current measurements are essential.

In advance, implementing appropriate measures such as filtering, signal conditioning, and calibration to mitigate inaccuracies and minimize noise in the sensor output. Additionally, exploring alternative sensors or supplementary techniques for low current scenarios may be warranted to ensure the desired level of accuracy in diverse operating conditions.

ACKNOWLEDGEMENT

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for all the support given.

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