Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

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Abstract

This project proposes the development of a low-cost, non-invasive energy monitoring system designed to measure and analyze electrical consumption in real time. Based on the SCT-013 current sensor and the principle of electromagnetic induction, the system detects current flow without direct contact, enhancing safety and accessibility. An Arduino microcontroller processes the analog signal to estimate current and energy cost, while an ESP32 module transmits the data wirelessly using the MQTT protocol. This architecture enables real-time access via mobile applications, web dashboards, and local LCD displays. The goal is to increase awareness of energy consumption, reduce unnecessary usage, and offer an affordable alternative to commercial smart meters. The final prototype successfully demonstrated functional, accurate, and secure operation, while maintaining a significantly lower cost than comparable market devices. Tests confirmed reliable data transmission and user-friendly interface, validating its potential for residential, commercial, and educational applications. However, limitations include dependence on network availability for full remote access and there is little interference derived from external magnetic field. Additionally, the system currently supports single-phase measurements only. Future developments may include three-phase support, integration with cloud-based analytics, and the application of machine learning for consumption pattern prediction. Broader implementation could also focus on scalability for use in underserved communities or remote areas with limited infrastructure. Overall, the project aligns with the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy), by fostering energy efficiency, environmental awareness, and technological inclusion through a practical, low-cost solution.

Keywords: energy monitoring, IoT, MQTT, SCT-013, Arduino, ESP32

Introduction

Currently, electricity is an essential resource for our society, powering virtually every aspect of modern life. From household lighting to the operation of large industries and infrastructure, it serves as the driving force behind technological and social development (Emanoel, 2023). Without electricity, many of the advancements that shape our daily lives would simply not exist. However, the increasing demand for electricity, combined with high production costs in Brazil, has made its availability an ever-growing challenge (Adrade, 2024; Pfeifer, 2018).

Furthermore, the urgent need to reduce environmental impacts places energy efficiency at the center of contemporary discourse (Pfeifer, 2018). In this context, climate change directly affects the efficiency of several renewable energy sources (Bento, 2024; Bitencourt, 2024). On September 19th 2024, in Rio de Janeiro, the Electric Sector Monitoring Committee (CMSE) convened representatives from key agencies, including the Ministry of Mines and Energy, the National Electric Energy Agency (ANEEL), the National Agency of Petroleum (ANP), the Electric Energy Trading Chamber (CCEE), and the Energy Research Company (EPE), as well as technicians from the National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) and the National System Operator (ONS). The meeting aimed to discuss, among other topics, the possible reintroduction of daylight-saving time, in response to the country's ongoing energy generation crisis. The measure was proposed by ONS, which reported difficulties in meeting the growing demand for electricity (Andrade, 2024; Bitencourt, 2024; Rodrigues, 2024; Steil, 2024).

According to CEMADEN, rainfall measurements since 1950 indicate that Brazil is experiencing one of the driest periods in its recent history. As a result, the generation capacity of hydroelectric plants has been reduced, forcing the country to turn to alternative sources (Steil, 2024). Additionally, due to the unpredictability of wind patterns, ONS states that it is not feasible to fully rely on wind energy to meet demand (Bitencourt, 2024). Consequently, Brazil has increased its reliance on thermoelectric plants, which burn fossil fuels such as coal, natural gas, and petroleum derivatives, significantly raising energy costs and impacting consumers (Andrade, 2024; Bitencourt, 2024; Rodrigues, 2024).

The proposed return of daylight-saving time aims to mitigate the effects of the so-called "ramp effect," a period of peak energy demand between 6 p.m. and 7 p.m. (Andrade, 2024). During this window, almost the entire thermoelectric system is activated, which, according to the Minister of Mines and Energy, Alexandre Silveira, directly influences final costs for consumers. The reinstatement of daylight-saving time could relieve pressure on the National Interconnected System (SIN) by extending solar energy production and reducing reliance on thermoelectric plants, while also encouraging the use of natural light, decreasing the need for electric appliances (Bitencourt, 2024).

According to ONS, adopting daylight saving time could reduce peak electricity demand in Brazil by up to 2.9% (Andrade, 2024). Moreover, thermoelectric plants not only pollute the environment but also raise the marginal cost of operation (CMO) to R$1.248/MWh (US$224.14/MWh), whereas the cost before their activation was below R$500/MWh (US$89.80/MWh) (Bitencourt, 2024). ONS estimates that reinstating daylight-saving time could generate savings of up to R$400 million (approximately US$71.8 million) between October 2024 and February 2025, benefiting both the government and the population by lessening the impact of electricity cost increases (Andrade, 2024).

These challenges are directly related to our project and to the United Nations' 2030 Agenda, particularly Sustainable Development Goal (SDG) 7, which aims to ensure universal access to reliable and modern energy services, increase the share of renewable energy in the global energy matrix, and promote international cooperation in clean technologies (United Nations Brazil, 2024). Our project also seeks to improve energy infrastructure, making it more sustainable and efficient.

In response to this scenario, we developed an electrical energy monitoring system capable of analyzing real-time data and identifying waste. By enabling industries, businesses, and households to monitor their energy consumption, we promote financial savings while helping to mitigate the “ramp effect,” which occurs when people return home and activate appliances between 6 p.m. and 7 p.m. Additionally, the system contributes to environmental preservation by fostering awareness regarding the efficient use of energy resources (Rovere, 2016).

Our system utilizes a non-invasive current sensor that measures the magnetic field variation around a conductive wire and converts this data into a current proportional to the original (Demetras, 2017). This current is then transformed into signals that can be processed by an Arduino microcontroller, which interprets the readings (Demetras, 2017). The data is subsequently transmitted over a network, where the Arduino communicates with an ESP32—a more advanced microcontroller with higher processing capacity. The data can be accessed via a real-time application from anywhere in the world, enabled by the MQTT protocol, which ensures efficient data transmission to an external server (Bulhões, Lomba & Neri, 2019). MQTT is crucial to our project, as it enables fast and reliable communication between devices: the ESP32 publishes the collected data to the server, and connected devices can subscribe to topics to receive this information in real time (Bulhões et al., 2019). Designed to optimize bandwidth use and reduce power consumption, MQTT is ideal for Internet of Things (IoT) applications like ours, where efficiency and reliability are essential (Bulhões et al., 2019; EMQX Team, 2024).

The proposed project emerges as a solution to the current challenges in the energy sector (Rovere, 2016; Pfeifer, 2018). It aims to promote energy efficiency at both residential and industrial levels, helping to reduce costs and environmental impact (Rovere, 2016; Pfeifer, 2018). By focusing on real-time waste identification, the system empowers users to make immediate and informed decisions, optimizing energy use in a practical and accessible manner (Rovere, 2016; Pfeifer, 2018). The innovation of the project lies in three core aspects. First, the use of the MQTT protocol enables real-time, remote, and global visualization of consumption data, allowing integration with IoT systems and multiple display formats such as LCD panels, MQTT dashboards, and web-based interfaces (Bulhões et al., 2019). Second, the non-invasive SCT-013 current sensor ensures precise and reliable current measurements, while also allowing safe and easy installation without the need for direct wiring intervention, thereby avoiding electric shocks or accidental discharges (Demetras, 2017). Third, the entire system is built with affordability in mind—its cost is significantly lower than comparable commercial monitoring devices, making it accessible to users of all income levels and geographic regions. Ultimately, this combination of precision, accessibility, and remote functionality results in a fully operational and scalable prototype aligned with sustainable energy goals. In this way, the project not only improves energy management but also strengthens the commitment to sustainability. Aligned with the UN's 2030 Agenda, specifically SDG 7, it demonstrates how simple and modern technologies can facilitate access to more sustainable energy consumption, raise awareness of efficient practices, support natural resource preservation, and reduce dependence on polluting sources such as thermoelectric plants (United Nations Brazil, 2024). This project proposes an integrated and affordable system to promote energy efficiency through technological accessibility and real-time monitoring.

Literature Review

Theorical Foundation

Electric Current

Electric current is a physical quantity that exists in two forms: alternating current (AC) and direct current (DC). It is defined as the rate at which electric charges—specifically electrons—flow through a conductor due to a difference in electric potential. Mathematically, this relationship is expressed as:

$$i = \frac{dQ}{dt}$$

where i is the electric current in amperes (A), Q is the electric charge in coulombs (C), and t is time in seconds. This equation describes the instantaneous current as the derivative of charge with respect to time, aligning with the continuous nature of electric flow in real systems.

According to the International System of Units (SI), electric current is measured in amperes, and electric charge is measured in coulombs.
(Adapted from Helerbrock, 2024)

Direct Current

Direct current (DC) refers to the unidirectional flow of electrons. It can be generated by cells or batteries that have a positive and a negative terminal. Its application is quite common in batteries and basic power supply systems. (Helerbrock, 2024)

Alternating Current

(Helebrock, 2024) Alternating current (AC) exhibits a different type of electron flow compared to direct current (DC). It routinely reverses direction due to periodic changes in the polarity of the conductor's potential, causing electrons to oscillate in place at a specific frequency measured in hertz (Hz), as seen in Figure 01. This type of current experiences less energy loss due to heat dissipation in the conductor. Its applications are widespread, including electric motors, industrial machinery, and household appliances.

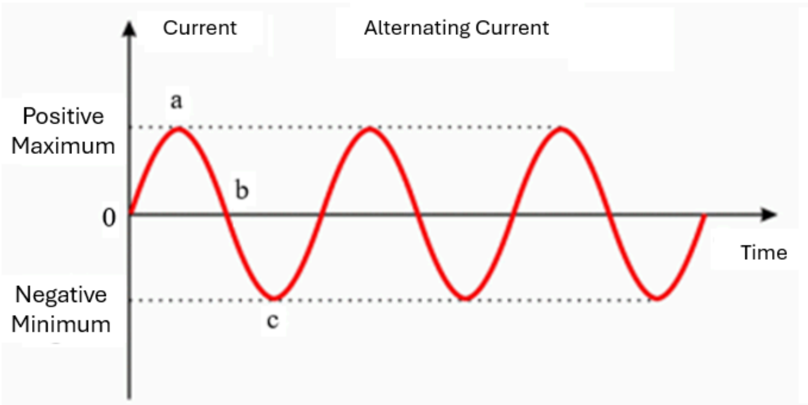

Figure 01 – Graph of the behavior of alternating current over time.
Source – (Demetras, 2017)

Electrical Resistance

Electrical resistance is a fundamental physical property of materials that opposes the flow of electric current. As current encounters resistance within a conductor, part of the electrical energy is transformed into thermal energy due to collisions between electrons and atoms. The unit of resistance is the ohm (Ω).

The relationship between voltage V, current i, and resistance R is formally described by first expression of Ohm's Law:

$$R = \frac{V}{i}$$

This expression models the behavior of resistive components under steady-state conditions, where V is the electric potential difference (in volts), i is the current (in amperes), and R is the resistance (in ohms).

Furthermore, the electrical resistance of a conductor is determined not only by its intrinsic material properties but also by its geometric dimensions. This relationship is described by the generalized form of Ohm's Law, often referred to as the second expression of Ohm's Law, and is given by:

$$R = \rho \cdot \frac{L}{A}$$

where R is the resistance (in ohms, Ω), ρ is the electrical resistivity of the material (in ohm-meters, $\Omega \cdot m$ Ω·m), L is the length of the conductor (in meters), and A is its cross-sectional area (in square meters). This equation shows that resistance increases with length and resistivity and decreases with a larger cross-sectional area. (Adapted from Melo, 2024)

Electric Voltage

Electric voltage is a scalar physical quantity that generates electric current by exerting an electromotive force on electric charges. In other words, it drives electrons through a conductive path, enabling the flow of current. Voltage represents the electric potential energy per unit of charge and is measured in volts (V) according to the International System of Units (SI). When two points in a circuit have different electric potentials, a potential difference is established. This difference causes positive charges to move toward regions of lower potential, and negative charges (such as electrons) to move toward higher potential. In a resistive circuit, voltage V, along with electrical resistance R, determines the current i according to first expression of Ohm's Law:

$$V = iR$$

This fundamental relationship explains how voltage drives current through a resistive medium. (Adapted from Helerbrock, 2024)

Magnetic Field

A magnetic field is generated by the motion of electric charges, particularly when an electric current flows through a conductor. This movement induces a field in the surrounding space, forming a region in which magnetic forces act on other moving charges or magnetic materials.

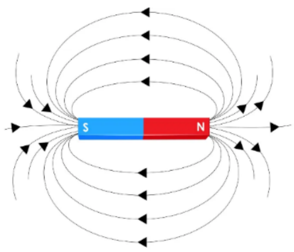

Figure 02 – Magnetic field line vectors
Source – (Helerbrock, 2024)

The magnetic field does not exert a force on stationary charges, but it influences the trajectory and acceleration of moving ones, effectively enabling their displacement through the Lorentz force. The intensity of the magnetic field is measured in teslas (T), the SI unit that quantifies the strength of magnetic induction. The direction and structure of the field are often represented by magnetic field lines, which emerge from the north magnetic pole and curve toward the south magnetic pole, as seen in Figure 02. The density of these lines indicates field strength: the closer the lines, the stronger the field at that point. For a long, straight conductor carrying current, the magnitude of the magnetic field at a radial distance r from the wire is given by Ampère's Law in its simplified form for cylindrical symmetry:

$$B = \frac{\mu_0 I}{2\pi r}$$

where B is the magnetic field in teslas, $\mu 0$ is the vacuum permeability constant. I is the current in amperes, and r is the radial distance from the wire in meters. This relationship is fundamental in understanding the inductive principle used in non-invasive current sensors like the SCT-013, which detect the magnetic field surrounding a conductor without requiring direct contact. (Adapted from Helerbrock & Melo, 2024)

Electromagnetic Induction

According to Faraday's Law of Electromagnetic Induction, a time-varying magnetic flux through a closed loop induces an electromotive force (EMF), which manifests as an electric voltage across the conductor. This induced voltage can, under appropriate conditions, produce a new electric current:

$$E = -\frac{d\Phi_B}{dt}$$

where E is the induced EMF (in volts), and Φ_B is the magnetic flux, defined as

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

representing the product of the magnetic field $\vec{B}$ and the area it penetrates. Conversely, Ampère's Law states that any electric current produces a magnetic field around the conductor, and the strength of this field is directly proportional to the current magnitude. This fundamental interaction enables the use of inductive devices for current sensing.

In practice, this phenomenon is observed in coils—spiraled conductive wires forming loops—where the changing magnetic field of a nearby conductor induces a measurable voltage. This principle underpins the operation of non-invasive current sensors, such as the SCT-013, which can detect current flow by analyzing the induced voltage in a coil surrounding the conductor, without requiring direct electrical contact. In our system, we apply this principle as the core mechanism for monitoring electrical energy consumption, enabling safe, accurate, and real-time current measurement through electromagnetic induction. (Adapted from Helerbrock, 2024)

SCT-013 Current Sensor

Now that we have defined electric current, resistance, voltage, magnetic field, and magnetic induction, it is possible to establish the foundation of the project.

The monitoring of electrical energy consumption is carried out using the non-invasive current sensor – SCT-013 – which utilizes the physical phenomena described above to measure the electric current flowing through a conducting wire (Pfeifer, 2018). This device is a type of non-invasive current transformer, eliminating the need to interrupt the circuit being measured (Pfeifer, 2018). Its structure consists of a split-core coil, as shown in Figure 03, that precisely captures variations in the magnetic field (Demetras, 2017; Pfeifer, 2018).

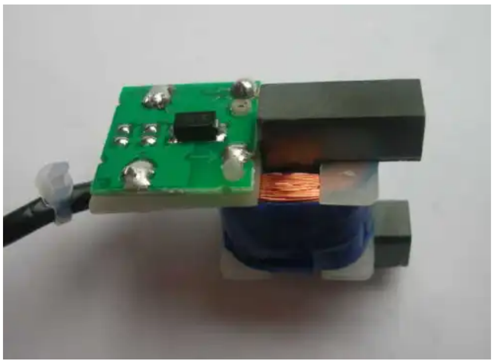

Figure 03 – Internal structure of an SCT-013 sensor.
Source – (Demetras, 2017)

Its operation is described by the principle of electromagnetic induction, according to Faraday's Law. When alternating current (AC), illustrated in Figure 01, passes through a conductor, it creates a varying magnetic field around it. The coil partially surrounds the conductor, capturing the variations of this magnetic field. This variation induces a proportional current inside the sensor, as seen in Figure 04, which is used to determine the current flowing through the main conductor. (Demetras, 2017; Pfeifer, 2018)

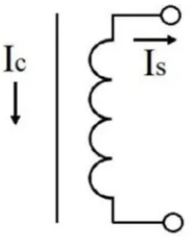

Figure 04 – Diagram illustrating the measured current (Ic) and the generated current (Is).

Source – (Demetras, 2017)

(Pfeifer, 2018) In the Figure 04, Ic represents the current being measured, while Is is the new proportional current generated. (Demetras, 2017) To read the data collected from the sensor, it is necessary to integrate it with an Arduino—a microcontroller that converts the data for reading. The SCT-013 sensor outputs an AC current signal that oscillates around zero, including negative voltages, which can be shown in Figure 05. However, since the Arduino can only read positive voltages (0–5V) on its analog input, the signal must be shifted upward.

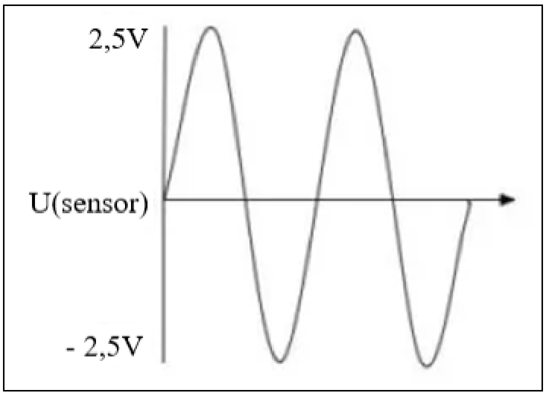

Figure 05 – Alternating current graph (-2.5V to +2.5V).
Source – (Demetras, 2017)

To accomplish this shift, a voltage divider circuit is used, which is seen in Figure 06. It creates a midpoint bias voltage of 2.5V. The sensor's AC voltage is then superimposed on this bias point, resulting in a waveform that oscillates around 2.5V — staying entirely within the Arduino's 0–5V range. This allows the full waveform, including what was originally negative, to be read accurately.

The signal conditioning circuit consists of:

- A 100µF electrolytic capacitor, which filters and stabilizes the bias voltage.
- Two 10kΩ resistors forming the voltage divider.
- A 33Ω burden resistor, which converts the current output from the SCT-013 into a proportional voltage.

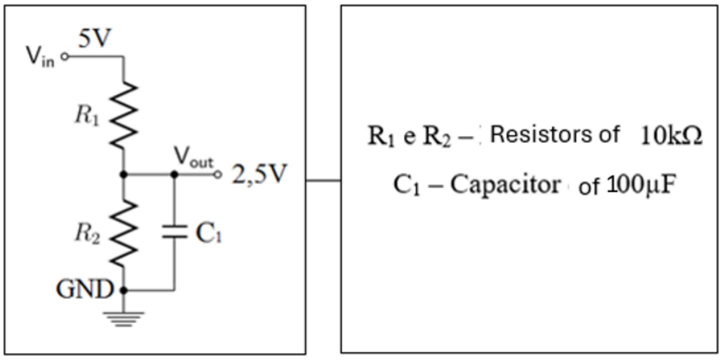

Figure 06 – Voltage divider scheme.
Source – (Demetras, 2017)

However, before connecting the signal to the voltage divider, it is essential to add a load (burden) resistor directly across the SCT-013 output terminals, as seen in the electrical diagram of Figure 07. This is necessary because the SCT-013 outputs current, not voltage — and a resistor is required to convert that current into a measurable voltage.

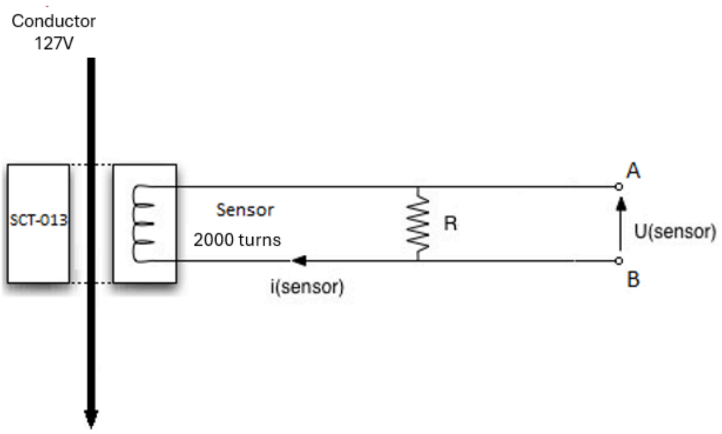

Figure 07 – Electrical diagram of the SCT-013 sensor in parallel with the calibration resistor.
Source – (Demetras, 2017)

To ensure the resulting voltage signal remains within the Arduino's 0–5V analog input range after biasing, the peak output voltage should not exceed ±2.5V.

$$R = V\,(\text{analog input} / 2) / I\,(\text{sensor}) = 2{,}5\ V / 0{,}0707\ A = 35{,}4\ \Omega.$$

The resistance, which we calculate multiple times further, is calculated using the first expression of Ohm's Law.

These values correspond to currents up to 100 A. Therefore, we selected a load resistor of 33 Ω, the closest resistor value in the market.

The final result is a voltage waveform that remains entirely positive (0–5V) and proportional to the current in the wire, ready to be read by the Arduino's analog input.

The complete electric circuit is configured as illustrated in Figure 08 and Figure 09.

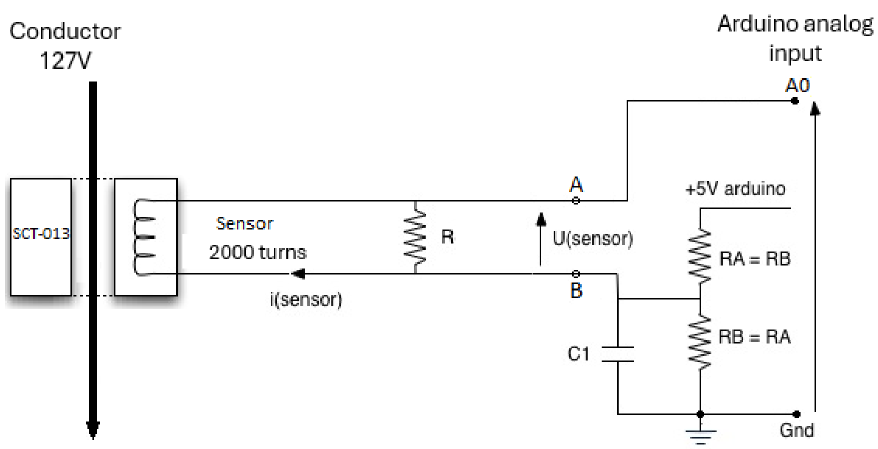

Figure 08 – Final Electric circuit
Source – (Demetras, 2017)

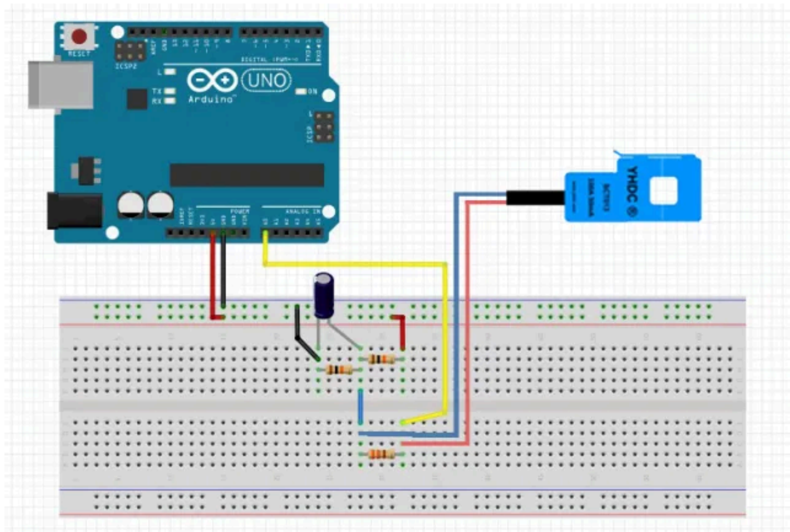

Figure 09 – Electrical schematic of the AC to DC voltage converter circuit.
Source – (Demetras, 2017)

For our measurements, it is necessary to program the Arduino to perform the conversion.

We initialize Arduino's serial communication, where 9600 (baud rate) refers to the number of bits transmitted or received per second.

(Demetras, 2017) The EmonLib library is responsible for performing the necessary conversion calculations. To do this, the current sensor must be initialized with a calibration value based on the resistor configuration used.

R = V (analog input / 2) / I (sensor) = 2.5 V / 0.0707 A = 35.4 Ω (closest resistor value in the market: 33 Ω)

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 33
CalibrationValue = 60.606

The line code to initialize with the corresponding calibration value is
SCT013.current(pinSCT, 90.909);

It is important to note that this calibration value is used with Arduino, which has a 5V analog input.

The entire code to print data at Serial Monitor is available here: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Arduino_test_Serial_print_example

The sensor must strictly be connected to only one of the wires of the measured conductor (either phase or neutral). If both the phase and neutral wires pass together through the sensor, the current will flow through one wire in one direction and return through the other in the opposite direction, generating opposing magnetic fields that cancel each other out. In this case, the meter will register zero current, making it impossible to perform the measurement.

Arduino and ESP32 Synchronization

The initial objective of the project was to avoid using Arduino and instead rely solely on the ESP32, a microcontroller with greater processing power and a wider range of features. This choice was made to enable the integration of our system with a data analysis interface, allowing users to monitor their electricity consumption at any time and from anywhere in the world.

(Makyama, 2019) Advantages of integrating the ESP32 into the project:

- **High Processing Capacity:** The ESP32 features a dual-core processor with speeds up to 240 MHz, enabling rapid processing of large volumes of data collected by the current sensor.

- **Built-in Wi-Fi and Bluetooth Connectivity:** Integrated Wi-Fi allows the ESP32 to connect to local networks or the internet, facilitating data transmission to external servers and applications. Bluetooth functionality enables communication with nearby mobile devices, allowing quick configuration and local data transfer when necessary.

- **Compatibility with the MQTT Protocol:** (Martins & Zem, 2016) The ESP32 supports the MQTT protocol, which is highly efficient for data transmission in

IoT applications. MQTT allows lightweight and fast communication, essential for real-time energy consumption data transmission. This compatibility ensures the system can continuously and reliably send and receive data, minimizing delays and maximizing communication efficiency.

- **Expandable Storage and Memory Capacity:** With internal flash memory and support for expansion, the ESP32 can temporarily store large amounts of data in case of connection interruptions with the server, preventing the loss of important information.

The storage capacity allows the implementation of local algorithms for data pre-processing, reducing the amount of information sent to the cloud and saving bandwidth. (Makyama, 2019) To achieve the goal of using only the ESP32, we performed the necessary calculations to calibrate the load resistor in the circuit. As the ESP32 analog input voltage is just 3.3V, we made calculations with a different value than that of Arduino and with another voltage driver circuit.

R = V (analog input / 2) / I (sensor) = (1.65 V) / 0.0707 A = 23.33 Ω (closest resistor value in the market: 22 Ω).

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 22
CalibrationValue = 90.909

Therefore, the sensor initialization should include the newly calculated calibration value.

```
SCT013.current(pinSCT, 90.909);
```

However, our tests conducted with the ESP32 were unsatisfactory, as the measured values did not closely match the actual values. Conversely, tests performed with the Arduino yielded current measurements that were much closer to reality.

Our team decided to still integrate the ESP32 into the project: we perform the measurement and data conversion using the Arduino and current sensor, then establish communication between the two microcontrollers. This approach allows the ESP32 to manage the network and, consequently, provide remote access for users to view the measured data.

Serial Communication

Thus, the new phase of the project involved synchronizing the Arduino and the ESP32. To achieve such synchronization, we employed the UART (Universal Asynchronous Receiver/Transmitter) digital communication method, which allows data exchange between two devices (Nunes, 2022; Pfeifer, 2018).

Main Characteristics:

1. **Asynchronous:** It does not require a shared synchronization clock between devices. Instead, data is transmitted with fixed format and baud rate, and the receiver must recognize and interpret the timing based on these parameters.

2. **Data Transmission:** Data is transmitted bit by bit in sequence. This can be done in two ways:
   - **TX** (Transmission): The device **sends** data.
   - **RX** (Reception): The device **receives** data.

Operation:

1. **Data Transmission:** The transmitter sends a data byte preceded by a start bit and followed by stop bits. The data byte is sent bit by bit, starting with the least significant bit.

2. **Data Reception:** The receiver waits for the start bit, then collects the data bits and stop bits to reconstruct the original byte.

Thus, the project code must be adjusted to establish serial communication. We added a new library, SoftwareSerial, through which we set the RX and TX pins, corresponding respectively to the Receiver and Transmitter. (Nunes, 2022)

```
SoftwareSerial serialBT(2,3);// RX(Arduino)-3 e TX(Arduino)-2
```

Now, the Arduino's serial initialization is performed, and its data transmission speed is set to 9600 bits per second:

```
serialBT.begin(9600);
```

To transmit data to the ESP32, we send the collected data via UART using the print command.

```
serialBT.print(current);
```

However, it is necessary for the ESP32 to receive the data. We initiated two separate serial communications: one to receive data from the Arduino (Serial2.begin), and another to send data to the computer (Serial.begin) for viewing via the Arduino IDE's serial monitor.

```
Serial.begin(9600); // Initializes serial communication with the computer's serial
monitor at a baud rate of 9600.
```

```
Serial2.begin(9600, SERIAL_8N1, 18, 5); // RX(ESP32)-D18 and TX(ESP32)-D5
```

(Nunes, 2022) Subsequently, we implemented a standard program to receive data sent by the Arduino and received by the ESP32, adjusted with our own variables.

This code is detailed here: https://github.com/Peagudoo/Monitoring-Project-Code/blob/b978bf0b2189e62114fa00f6bf7182c91115bbd6/ESP32_RecieveData-FromArduino_example

Thus, the connection between the Arduino and ESP32 was established. To make the data stored in the memory of both microcontrollers available in a user-friendly interface, we used the MQTT protocol, which is responsible for storing data on an external server connected to the network. Accordingly, the ESP32 transmits the data to the network, and an application collects these data on its interface, allowing the user to access information about their electricity consumption. (Bulhões et al., 2019)

MQTT Protocol

The MQTT protocol establishes communication between client and server, where the client can both store and receive data. This is achieved through a Publish-Subscribe method, which involves a Broker—an intermediary information server that receives data sent from sensors, manages it, and shares it according to the client's needs, as could be seen in Figure 10.

The client acts in two distinct roles: as a Publisher (posting data) and as a Subscriber (receiving data). The relationship between the client and the Broker functions such that the Broker organizes received information in a hierarchical system according to topics. Clients can subscribe to the topics they wish to receive; however, the Broker manages the requests, so the client and Publisher do not communicate directly, thereby maintaining anonymity for both parties. (Bulhões et al., 2019; Martins & Zem, 2016)

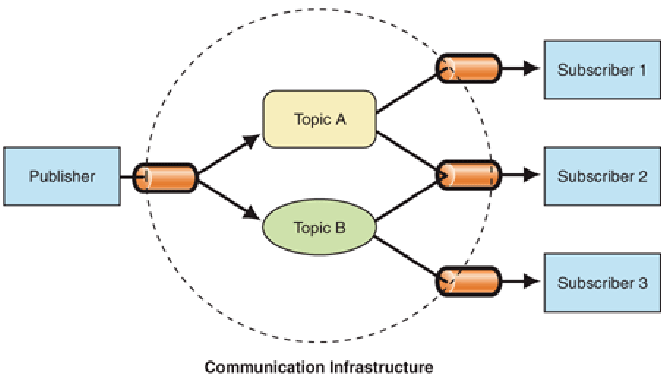

Figure 10 – Communication diagram using the MQTT protocol.
Source - (Bulhões et al., 2019)

In our project, the following topics are used: electric current, energy, cost, and power, with each item representing a specific topic. The Publisher is the ESP32, which, upon receiving data collected from the Arduino, sends it to the Broker. The client is the application, which requests data from the Broker, and the Broker in turn delivers the data.

Advantages of the MQTT Protocol:

- Low memory consumption.
- Low processing requirements.
- Low bandwidth usage.

(Martins & Zem, 2016)

Since the Publisher does not send information directly to clients, it does not need to store client information or send multiple copies of data—only the specific data requested. Additionally, only information related to the Broker, its topics, and packet transmissions is stored. For these reasons, MQTT is excellent for IoT applications, providing a low-cost and accessible solution for projects handling moderate amounts of data. (Bulhões et al., 2019; Martins & Zem, 2016)

Methodology

Prototype Development

The first step in building the prototype was to determine the installation location for the entire electrical circuit assembly. Additionally, to perform the measurements, we chose to use circuit breakers, as shown in Figure 11, to simulate the electrical panel of an establishment, where the user would monitor their electricity consumption. Thus, the project is designed with four circuit breakers: the first is responsible for supplying the entire electrical current to the establishment, allowing total consumption measurement using only one non-invasive current sensor. The remaining three circuit breakers are designated to measure specific electrical appliances as desired by the user.

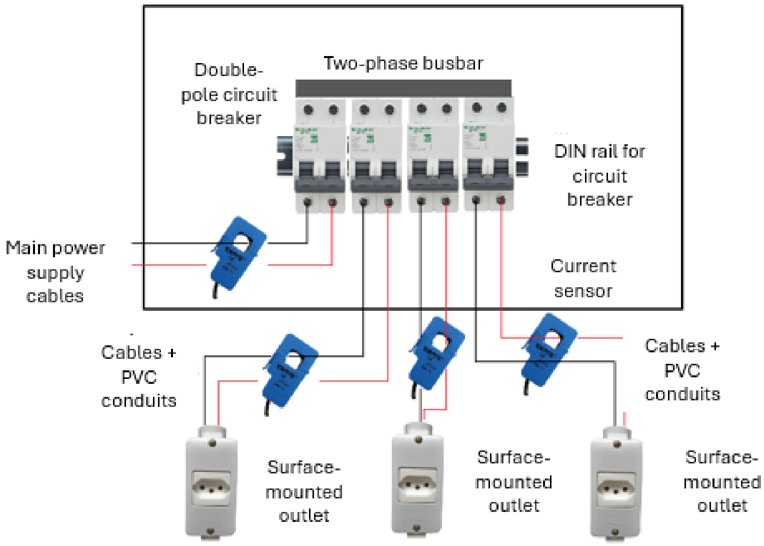

Figure 11 – Initial sketch of the project.
Source - AUTORS

The first step in assembling the panel was to mount the power box and the circuit breakers, as seen in Figure 12. These were connected with wiring linked to the outlets. The non-invasive current sensors are clamped around the wiring to perform the measurements. The power box houses the electrical circuit for each sensor, which in turn is connected to the Arduino.

As a secondary method to display the data collected by the current sensors, we decided to use four LCD displays, each corresponding to its respective sensor connected to the circuit breakers. For this purpose, we laser-cut a mounting structure for each display, which was then installed on the panel next to the outlets, as demonstrated in Figure 12.

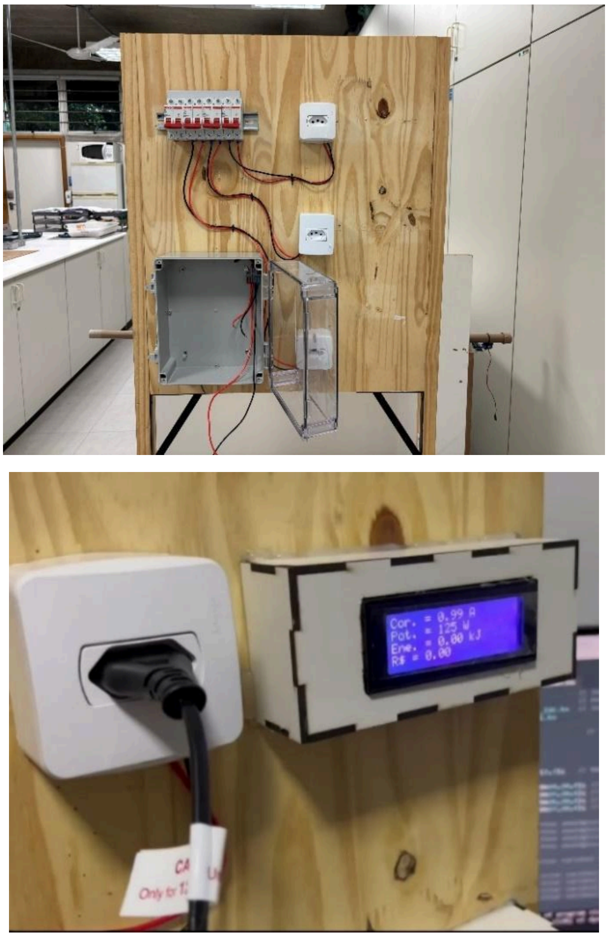

Figure 12 – Image of the wooden panel and the power box (left), as well as the display. LCD to display real-time readings (right).
Source – AUTORS

Next, we installed a switched-mode power supply responsible for converting the 127 V AC input from the power source into 12 V DC output. However, it was necessary to install a voltage regulator (with a 12 V input and 6.5 V output) to prevent overheating or damage to both the Arduino and the ESP32.

We then designed the electrical circuit so that the resistors, capacitors, and their connections were arranged on a breadboard (protoboard), while the Arduino and the ESP32 are housed inside the power box, as seen in Figure 13. The circuit connections to the four non-invasive current sensors extend outside the power box, allowing for measurement of the electrical conductor wires.

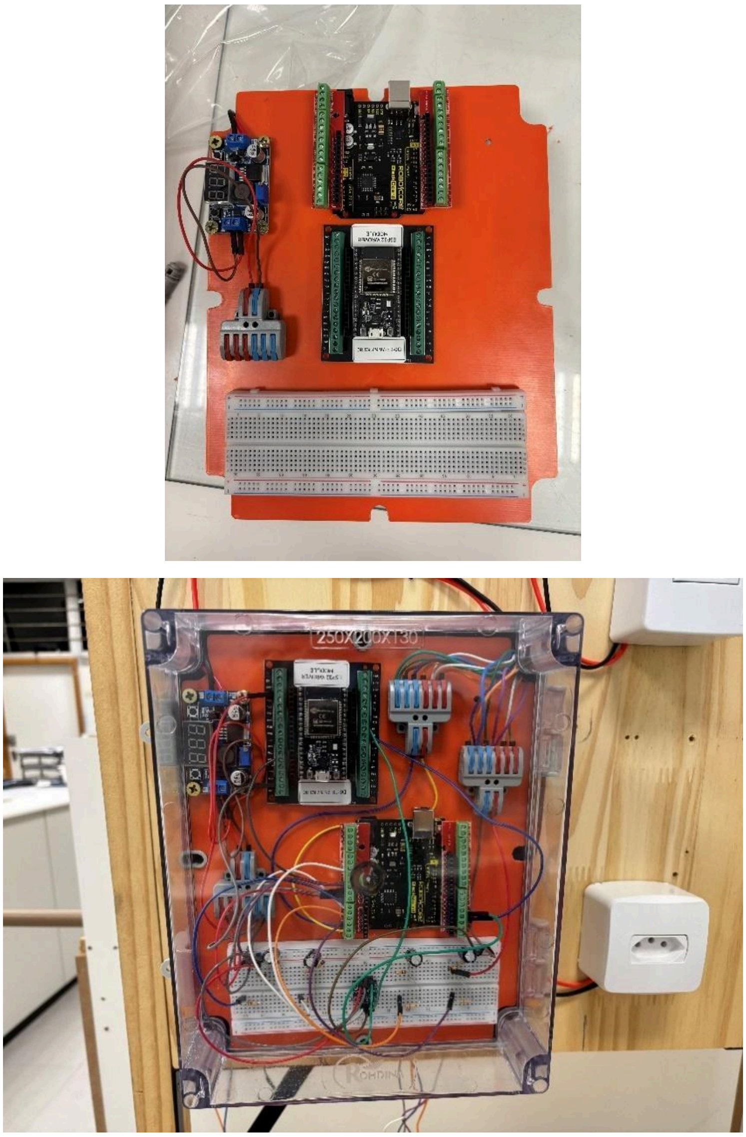

Figure 13 – Image of the electrical box, with its respective connections.
It is not possible to observe the current sensors and their connections in this image.
Source - AUTORS

The final electrical circuit was developed as follows: first, the main power is connected directly to the main circuit breaker (the first breaker), from which the 127 V AC voltage is distributed to three outlets where electrical appliances the user wishes to monitor can be plugged in individually. Simultaneously, the mains voltage is routed to the switched-mode power supply via a splice connector. This power supply converts the voltage to 12 V DC, which is then reduced to 6 V by the voltage regulator before being directed to power the Arduino, ESP32, displays, and breadboard.

Finally, we programmed all the code to synchronize the devices with each other: the Arduino, the ESP32, the SCT-013 current sensors, and the displays. These were also integrated with the MQTT protocol. Thus, we ended up with two final codes: one for the Arduino and one for the ESP32.

Arduino:
https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Final_Arduino_code

ESP32:
https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Final_ESP32_code

Testing

Our tests were conducted so that the results could be observed through three different means:

1. LCD Display
2. Application using the MQTT Protocol
3. Web Interface

LCD Display Testing

The use of the displays served as an interface to verify whether the acquired values corresponded to reality. For this purpose, we used a clamp ammeter—a device that also measures the current of a conductor—which allowed us to compare its readings with the data collected from our SCT-013 sensor. We then integrated the displays into the electrical circuit, as illustrated in Figure 14, and the code.

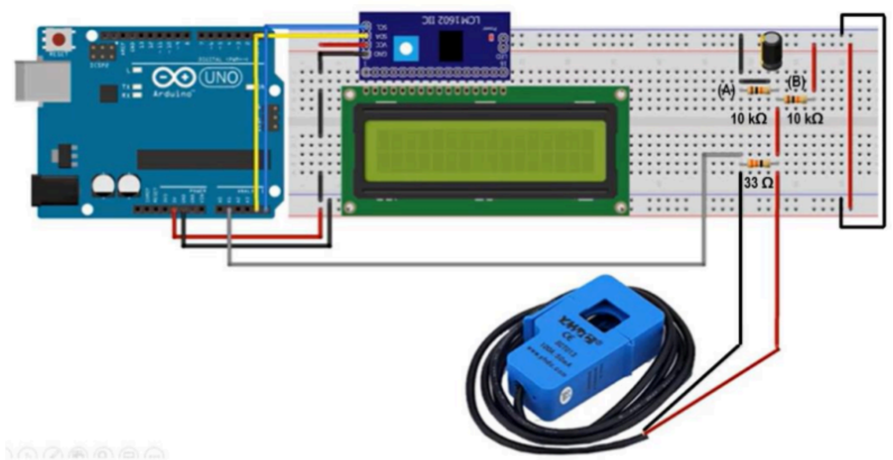

Figure 14 – Use of the LCD display to visualize data from the SCT-013.
Source – AUTORS

To program the display, the Arduino LiquidCrystal library is required.
The first step is to create the display object:

```
LiquidCrystal_I2C lcd1(adress, n_collumns, n_rows); //object that controls the LCD display.
```

The first parameter is the address, which the user defines to identify the display. The second parameter specifies the number of columns the display has, while the third parameter indicates the number of rows. In our case, we will use four displays, each with 20 columns and 4 rows.

```
LiquidCrystal_I2C lcd1(0x24,20,4);
LiquidCrystal_I2C lcd2(0x25,20,4);
LiquidCrystal_I2C lcd3(0x26,20,4);
LiquidCrystal_I2C lcd4(0x27,20,4);
```

To initialize the display and turn on its backlight, we use the commands lcd1.init(); and lcd1.backlight();, respectively (Makerhero, 2022). Since we have four variables to display, we assign each data type to a separate line. The code to initialize and print in LCD Displays is present here: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/LCD_Display_Printing_Example

Our initial tests aimed to analyze the error rate that the sensor could present compared to the clamp ammeter. For this purpose, we used only one display, one sensor, and the electrical device being measured. At this specific testing stage, the Arduino and ESP32 were not yet synchronized, as their communication was not necessary for the displays to function.

Tests 1 and 2 video conducted:
https://docs.google.com/presentation/d/1g2PTM-DydHYOpGwmlxD-8EwrBCoo0Fn9CAsPDr1ze9c/edit?usp=sharing

In Test 2, conducted with the soldering iron, it is possible to observe that the sensor provides readings even when no current is present. We believe this may have occurred due to external interference generated by electronic devices present in the testing environment (laboratory).

This hypothesis arose because, when tested in other environments outside the range of these electronic devices—such as at home—the sensor provided zero current readings when not measuring. Therefore, it is probable that the magnetic field from other electronic devices induced a response in the sensor, resulting in readings even though they were not from the conductor wire.

Application Testing using the MQTT Protocol

Once the synchronization between the Arduino and the ESP32 was completed, and the latter integrated with the MQTT protocol, testing with the application became possible. As mentioned earlier, the integration of the protocol enables remote monitoring of energy consumption from anywhere in the world at any desired time (Bulhões et al., 2019).

For this purpose, we used an iOS application called ON OFF, which allows the capture of data published on the external MQTT server. Thus, the application acts as the client, while the ESP32 functions as the Publisher.

The team decided that only data from the main circuit breaker (which measures the total electrical current of the establishment) would be displayed in the application during testing.

This link contains an MQTT video test: https://docs.google.com/presentation/d/1d3qZIVl55eJ1PHWbBPnyKwMF6CbK8FIfDjc_fjMUi6Q/edit?usp=sharing

Web Interface Testing

(Galvão, 2023) Through the ESP32, it is possible to integrate microcontroller data on the web, enabling users to also view their energy consumption on a server connected to the internet.

The code is available at the following link: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/WebServer_test_code

Test video with the web server:
https://docs.google.com/presentation/d/1n3twGLn_ofM23tX9RS8k1i5nGzYXelZxA8VGZgHaPw0/edit?usp=sharing

Results

We analyzed the margin of error for various electrical appliances and compiled these error rates into Table 01. Additionally, we created a comparative graph between the non-invasive current sensor and the clamp ammeter, as seen in Figure 15.

No.	Devices	SCT-013 (A)	Professional clamp ammeter (A)	Deviation	Margin of Error
1	Sterilair Air Purifier	0.26	0.25	0.01	4%
2	LG SmartTV	0.62	0.65	-0.03	-5%

3	Arno Fan (low power)	0.64	0.65	-0.01	-2%
4	Arno Fan (medium power)	0.82	0.82	0.00	0%
5	Arno Fan (high power)	1.07	1.08	-0.01	-1%
6	Blender (low power)	1.44	1.46	-0.02	-1%
7	Consul Refrigerator	1.60	1.63	-0.03	-2%
8	Blender (high power)	1.74	1.75	-0.01	-1%
9	Philco Vacuum cleaner	3.32	3.33	-0.01	0%
10	Conair Hair Dryer (low power)	3.45	3.50	-0.05	-1%
11	Philco Hair Dryer (high power)	4.35	4.38	-0.03	-1%
12	Conair Hair Dryer (high power)	6.22	6.30	-0.08	-1%
13	Philco Hair Dryer (high power)	8.20	8.40	-0.20	-2%
14	Cadence Electric Kettle	8.31	8.46	-0.15	-2%
15	Microwave Oven	12.14	12.70	-0.56	-4%

Table 01 – Comparative table with data collected from SCT-013 and professional clamp ammeter.
Source - AUTORS

The average margin of error is at most ±4%.

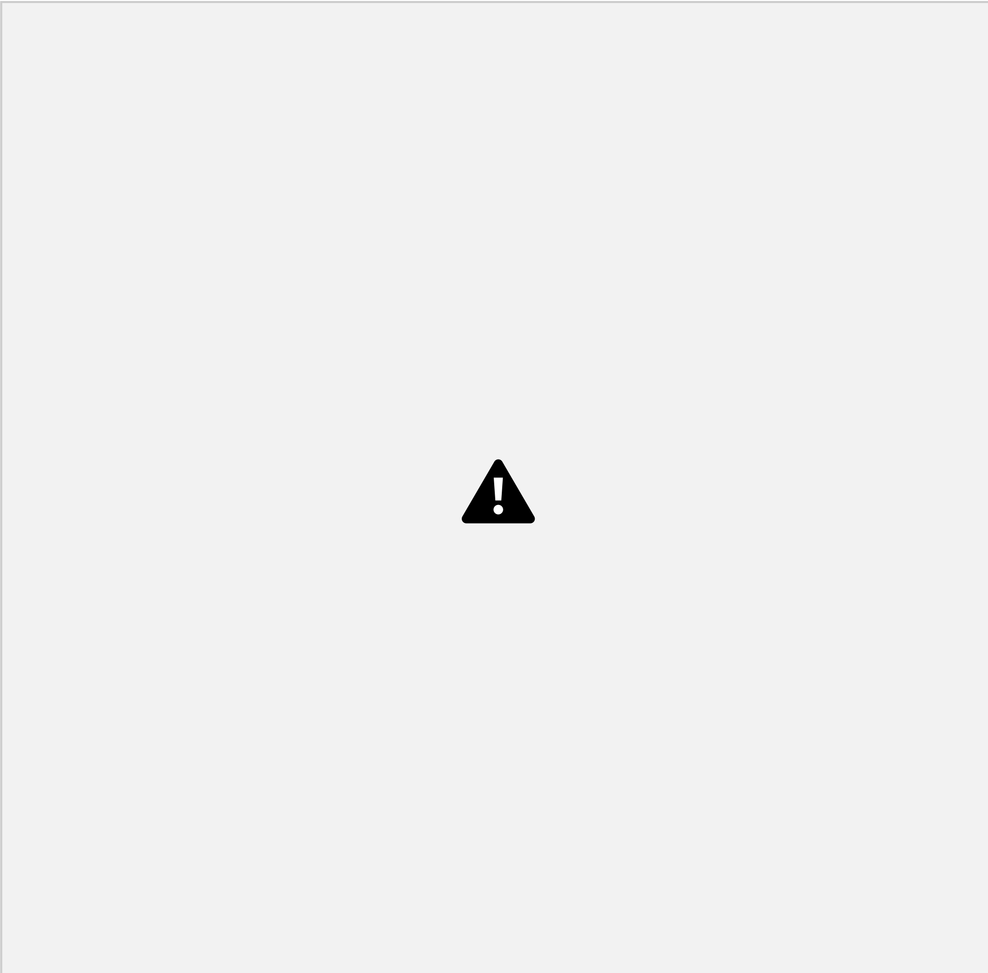

Figure 15 – Comparative graph between data read by the SCT-013 sensor and the professional clamp ammeter.
Source - AUTORS

We conclude that the error rate of the SCT-013 sensor compared to the clamp ammeter is relatively low, as illustrated in Table 01 and Figure 15. Therefore, the project demonstrates highly accurate results.

Project Costs

We conducted a cost analysis of the project for potential commercial application, as seen in Table 02, and we noted that the total cost differs from that of developing the prototype, look at Table 03. It is important to consider that the shopping was made in Brazil, and the total cost may vary for different countries.

Products	Price (R$ and U$)	Supplier

Non-invasive current sensor SCT-013	R$ 39.90/US$ 7.17	Mercado Livre
Switched-mode power supply 12 V DC output	R$ 34.65/US$ 6.22	Mercado Livre
20x4 LCD display	R$ 36.00/US$ 6.47	A2 Robotics
Protoboard	R$ 7.50/US$ 1.35	A2 Robotics
10KΩ Resistor	R$ 0.10/US$ 0.0018	A2 Robotics
33Ω Resistor	R$ 0.10/US$ 0.0018	A2 Robotics
Electrolytic capacitor	R$ 0.19/US$ 0.034	A2 Robotics
Arduino UNO	R$ 40.38/US$ 7.25	A2 Robotics
ESP32 WiFi and Bluetooth	R$ 43.90/US$ 7.89	A2 Robotics
Splice connector	R$ 11.55/US$ 2.07	Eletriza
Female P4 plug connector with terminal block	R$ 2.20/US$ 0.4	A2 Robotics
Voltage regulator	R$ 7.00/US$ 1.26	A2 Robotics
Total	R$ 223.47/US$ 40.14	---

Table 02 – Project cost table for commercial installation.
Source - AUTORS

Products	Price (R$ and U$)	Supplier	Quantity
Non-invasive current sensor SCT-013	R$ 39.90/US$ 7.17	Mercado Livre	4
Switched-mode power supply 12 V DC output	R$ 34.65/US$ 6.22	Mercado Livre	1
20x4 LCD display	R$ 36.00/US$ 6.47	A2 Robotics	4
Protoboard	R$ 7.50/US$ 1.35	A2 Robotics	1
10KΩ Resistor	R$ 0.10/US$ 0.0018	A2 Robotics	8
33Ω Resistor	R$ 0.10/US$ 0.0018	A2 Robotics	4
Electrolytic capacitor 100 µF	R$ 0.19/US$ 0.034	A2 Robotics	4
Arduino UNO	R$ 40.38/US$ 7.25	A2 Robotics	1
ESP32 WiFi and Bluetooth	R$ 43.90/US$ 7.89	A2 Robotics	1
Splice connector	R$ 11.55/US$ 2.07	Eletriza	3
Female P4 plug connector with terminal block	R$ 2.20/US$ 0.4	A2 Robotics	4
Power box	Reused	---	1
Mounting panel	Reused	---	1
Circuit breaker	R$ 8.85/US$ 1.59	Dimensional	4
Voltage regulator	R$ 7.00/US$ 1.26	A2 Robotics	1
Surface-mount outlet	R$ 9.17/US$ 1.65	Leroy Merlin	3

Clamp ammeter	R$ 34.58/US$ 6.21	Mercado Livre	1
TOTAL	R$ 579.93/US$ 104.15	---	

Table 03 – Complete project cost table.
Source - AUTORS

Limitations

As mentioned previously, the initial goal of the project was to use only the ESP32 to convert the data collected by the sensor and provide it on the network via MQTT.
However, despite performing the necessary calculations to configure the load resistor, the collected data were not sufficiently accurate.

R = V (analog input / 2) / I (sensor) = 1.65 V / 0.0707 A = 23.33 Ω.
The closest commercially available resistor to the calculated value is 22 Ω.

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 22
CalibrationValue = 90.909

Therefore, the sensor initialization should include the newly calculated calibration value.

```
SCT013.current(pinSCT, 90.909);
```

Even with the correct calibration values and load resistor configuration, we were obtaining inaccurate measurements. Therefore, we decided to perform data conversion and processing using Arduino. By synchronizing the Arduino with the ESP32, the latter receives the data and publishes it to the MQTT server, from which the application can subscribe to topics and act as a client (Bulhões et al., 2019; Martins & Zem, 2016).
Furthermore, the tests showed different margins of error for each electrical device measured, making it impossible to establish a general margin of error for the current sensor, as seen in Table 01 and Figure 15. Consequently, we collected data and created graphs, as shown in Figure 15, showing the specific deviation for each device measured.
Another important factor to consider is that the external environment slightly affects the results collected by the sensor. For example, when the sensor is not measuring current from a conductor wire, it may pick up magnetic fields emitted by nearby electronic devices. However, when there is an active current flow in the conductor, the sensor ignores this external interference and measures only the data from the intended device.

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Conclusion

Project Conclusion

In general, the group concludes that the electric energy monitoring project successfully achieved its main objectives, demonstrating it to be an efficient, accessible system capable of promoting awareness about energy consumption. By employing a non-invasive current sensor and technologies such as Arduino, ESP32, and the MQTT protocol, it became possible to monitor energy consumption in real time from anywhere with an internet connection, thereby helping to reduce waste and encouraging more responsible electricity use (Bento, 2024; Bulhões et al., 2019; Emanoel, 2023).

Furthermore, from a socio-economic perspective, the project holds great importance as it addresses a global issue: the efficiency in electrical energy use. By monitoring energy expenditure, users can identify major points of waste and adopt more effective measures to optimize consumption. In Brazil, where electricity costs can represent a significant burden on household budgets, especially for low-income families, this technology has the potential to generate a profound positive impact. Companies and other sectors that adopt this solution can also achieve greater energy efficiency, which translates into financial savings and enhances their market competitiveness (Bento, 2024; Emanoel, 2023).

However, like any project, our system has its advantages and drawbacks. Among its main advantages, accessibility stands out, as the project can be used by diverse audiences given that the materials employed have an affordable cost, evinced by Table 02 and 03. Additionally, safety is a strong point, since the use of the SCT-013 sensor avoids the need to directly interfere with electrical wiring, facilitating installation and eliminating the risk of electric shocks (Demetras, 2017). Another important aspect is innovation, since the solution enables remote and real-time monitoring of energy consumption through the integration of the ESP32 with the MQTT protocol, allowing consumption tracking from anywhere in the world (Bulhões et al., 2019). Finally, the project promotes sustainability by aligning with the United Nations Sustainable Development Goals (SDGs), especially SDG 7, by encouraging efficient energy use (United Nations Brazil, 2024).

On the other hand, the project presents some drawbacks, such as dependence on a stable internet connection, since remote monitoring relies on a constant internet connection for data to be transmitted correctly (Bulhões et al., 2019). In locations with limited network infrastructure, the system's effectiveness may be compromised. Another shortcoming is the absence of an alert system, as the current system does not issue notifications when energy consumption exceeds certain thresholds. Moreover, the project did not implement cloud-based analysis and active response due to the high demand of energy, which is highly recommended for applications in complex industrial systems.

Future Implementations

For future improvements, it is recommended to implement an alert system configured to send notifications when energy consumption exceeds predefined limits. Additionally, it would be beneficial to include the capability to collect and store historical consumption data in a cloud-based server, allowing for the tracking of trends over time and aiding more informed decision-making for long-term energy savings (Martins & Zem, 2016; Rovere, 2016). Furthermore, there is space for Artificial Intelligence (AI) implementation on evaluating data and taking actions of across energy consumption.

We still aim to use only the ESP32 for current measurements; however, this requires proper configuration of the resistors, which we have yet to determine. Finally, we intend to completely eliminate external interference caused by the electromagnetic congestion of electronic devices present in the environment by using a metallic shielding material to cover the current sensor relative to the external environment. This approach will enable measurement exclusively of the magnetic field generated by the conductor wire, thereby ensuring greater precision in the readings.

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Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

Overall comments: This is a generally well-written paper. The student addresses a timely and important subject. The student ties the relevance of their engineering project directly to a pressing problem. In order to supply a daily evening surge in power needs in Brazil polluting coal fired power plants need to be brought online. The author proposes instead reducing this demand through monitoring of where demand can be reduced using their device. The student engages with the literature to understand the broader problem and come to a first possible solution.

A weakness of this work is that there is no comparison or review of existing similar systems. I live in the UK and for some years we have a power monitoring device which shows us how much power we're using at any time, and the total cost. All these devices send data back to a base station. I think they use a mesh network. So each house connects to nodes in neighbouring houses. In this sense, such monitoring is not novel in the UK, though it might be unusual or uncommon in Brazil (I don't know).

If such devices are not common in Brazil then the paper should consider some review of what's common elsewhere (such as the UK). Why might their solution be better than what already exists? The difficulty with making the measurements directly with the ESP32 is a bit confusing for the reviewer.

I would recommend another round of review if all the comments, some major, some minor, can be addressed.

Specific Comments:

Introduction: Some text can be trimmed from the opening on the importance of electricity to society. Some extra details can be added which may be surprising to your readers not based in Brazil. Particularly relating to the change in weather patterns. You say rainfall is down, but being specific/precise adds value for the reader, this is what came up when I looked this up:

"Overall, Brazil has experienced a downward trend in average rainfall since around 1950. However, this trend is not uniform:

Northeast and other semi-arid areas are becoming drier.

Southern regions are seeing a recent uptick in rainfall.

Amazon is facing longer, more severe dry seasons and drought intensification. (20% less rainfall per decade)."

The last paragraph of the introduction could be less verbose as it repears information mentioned previously.

I'm not sure it's appropriate to include the information from the heading "Electric Current" to "Magnetic Field". All of this could/should be summarised with a few labelled equations.

"Now that we have defi ned electric current, resistance, voltage, magnetic fi eld, and magnetic induction, it is possible to establish the foundation of the project." --- text can be removed.

The author repeatedly mentions that their sensor method is "non-invasive". However, they are loading the other devices. Energy is being drawn from the main circuit. The biasing circuit is causing the "burden" resistor to constantly draw 70 mA.

Why not have a much larger "burden" resistor, reduce the current flow, and then divide down that voltage. How does the ambient temperature affect these measurements?

"These values correspond to currents up to 100 A. Therefore, we selected a load resistor of 33 Ω, the closest resistor value in the market." --- Unclear

"However, our tests conducted with the ESP32 were unsatisfactory, as the measured values did not closely match the actual values. Conversely, tests performed with the Arduino yielded current measurements that were much closer to reality." -- There is no discussion here of the accuracy with which tests were made. What was used to measure/verify voltage? Why did the ESP32 results not match expectations?

Figure 11 -- It looks like this may be taken from some source "Autors?". I believe to do this you need to get permission. Also, the attribution is not clear. The author should check all their figures and consider drawing/preparing their own figures from scratch to avoid such issues.

MQQT has been introduced but what do the letters represent?

"Simultaneously, the mains voltage is routed to the switched-mode power supply via a splice connector" -- It sounds like an electrician is required for installation. This sounds very expensive. Why not a battery powered device. The amount of power drawn by the "burden" resistor is what's required to run a microcontroller, why not inductively couple away some power and rectify it?

"Tests 1 and 2 video conducted:
https://docs.google.com/presentation/d/1g2PTM-DydHYOpGwmlxD-8EwrBCoo0Fn9CAsPDr1ze9c/edit?usp=sharing" -- The main results should be self contained within the paper.

Figure 15 is corrupted.

"In general, the group concludes that the electric energy monitoring project successfully achieved its main objectives, demonstrating it to be an effi cient, accessible system capable of promoting awareness about energy consumption" -- Certainly it can be said to raise awareness. Whether it's efficient or an optimal solution isn't really considered in the paper.

Title: Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

Final Recommendation: Accept with Major Revisions

This paper is an excellent student project that effectively combines theory, hardware, open-source code, and laboratory work. Once the authors integrate their work into the relevant academic literature, refine the experimental statistics, and ensure compliance with electrical safety requirements, it will serve as an inspiring and reproducible template for promoting affordable energy awareness. Additionally, it will advance the Convergence Journal's mission of empowering young researchers.

Review Feedback and Recommendations:

In general, the manuscript describes a low-cost, non-invasive energy-monitoring prototype that couples an SCT-013 current transformer with an Arduino for signal conditioning and an ESP32 for Wi-Fi transmission via MQTT. Some major strengths have been discussed in the paper, including accessibility and cost of the design, pedagogical value of exposition of Faraday' Law, system integration with different hardware, and validation of the prototype.

However, to achieve the standard as an accepted Convergence Journal paper, some revisions are required:

1) The literature context and presentations of the information need to be improved
The proposed draft paper, in its current form, reads more like an undergraduate dissertation or laboratory report than a concise journal article. The dissertation style features are displayed a lot in the paper, such as extensive book theory sections (AC/DC, definitions of Ohm, Faraday's Law, etc.), detailed instructions on building/testing stages, and photos of every stage. To meet the journal's expectations of context, it is highly recommended to shorten the theory introductions into 1 or 2 concise paragraphs with assumed prior knowledge. Replace the step-by-step instruction with a brief methods paragraph with a circuit diagram included. In addition, organized a summary of the figure or table of the overall cost, instead of the bill of materials with local prices
2) The accuracy of the experiments needs to be improved:
In the proposed draft paper, the error values are given without confidence intervals, sample size N=1 per load, and no discussion of phase-shift or temperature drift. To improve, to add some standard deviation across ≥ 3 repeated measurements, and include a short subsection on uncertainty budget (sensor tolerance, burden resistor, ADC resolution) is recommended.
3) Safety and ethics considerations need to be added:

In this paper, the device is intended for mains operation; however, clearance distances, fuse protection, and insulation class are not mentioned. Adding a paragraph with safety considerations, stating that the sensor is clamped on a single core only, and some other mandatory electronic requirements.

4) Scalability claims need to be confirmed with more evidence:

In this paper, the title promises “scalable IoT systems”, yet only single-phase, single-channel data are presented, however, no cloud ingestion rate, broker load test, or OTA firmware update is shown. It is highly recommended to provide a multi-channel expansion schematic and throughput test, or adjust the title to “… a Single-Channel Educational Prototype”.

5) Reference quality and formatting
   The reference should be numbered accordingly within the paragraphs, starting with the literature review part. Some sources do not seem to be presented in the **English version**, others are non-peer-reviewed resources with too many blog posts and tutorials, and journal and books page ranges and DOIs are inconsistent. 15 to 25 academic resources are recommended as an ideal number of references. The author could check the required submission format guidelines provided by the Convergence journal, especially on the citation styles and other formatting requirements, spacing, etc.
6) Some other minor points
   In this paper, the Abstract should quantify accuracy (± 5 %) and state the single-phase limitation upfront. The results and output also need to be double confirmed in the conclusion part. The picture sizes should be set up to match each other, and the resolutions also need to be checked. Repetitive “future work” laundry list last 2 pages, which could be shortened into a small paragraph with a few sentences to highlight the future research.

Remote Energy Monitoring via MQTT and SCT-013: A Single-Channel Prototype for IoT Systems

Author(s) Name Redacted for Peer Review
Institution Name (Redacted)
Submitted to Convergence Journal – July 2025

Abstract

This project proposes the development of a low-cost, single-phase non-invasive energy monitoring system designed to measure and analyze electrical consumption in real time. Based on the SCT-013 split core current transformer and the principle of electromagnetic induction, the system detects current flow without direct contact, enhancing safety and accessibility. An Arduino (10-bit ADC, 0–5 V reference) microcontroller processes the conditioned analog signal - converted across a 33 Ω burden resistor and biased to the ADC mid-point - to estimate instantaneous current and energy cost. Repeated measurements (N = 5) show a conservative accuracy of ±5% under the tested load conditions. An ESP32 module receives the data read by the Arduino over UART and transmits it wirelessly using the MQTT protocol. This architecture enables real-time access via mobile applications, web dashboards, and local LCD displays. The goal is to increase awareness of energy consumption, reduce unnecessary usage, and offer an affordable alternative to commercial smart meters. The final prototype successfully demonstrated functional, accurate, and secure operation, while maintaining a significantly lower cost than comparable market devices. Tests confirmed reliable data transmission and user-friendly interface, validating its potential for residential, commercial, and educational applications. However, limitations include dependence on network availability for full remote access and there is little interference derived from external magnetic field. Additionally, the system currently supports single-phase measurements only. Future developments may include three-phase support, integration with cloud-based analytics, and the application of machine learning for consumption pattern prediction. Broader implementation could also focus on scalability for use in underserved communities or remote areas with limited infrastructure. Overall, the project aligns with the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy), by fostering energy efficiency, environmental awareness, and technological inclusion through a practical, low-cost solution.

Keywords: energy monitoring, IoT, MQTT, SCT-013, Arduino, ESP32

Introduction

Currently, from household lighting to the operation of large industries and infrastructure, energy serves as the driving force behind technological and social development. However, the increasing demand for electricity and the urgent need to reduce environmental impacts, combined with high production costs in Brazil, has made its availability an ever-growing challenge (Andrade, 2024; Pfeifer, 2018; Scianni et al., 2013).

In this context, climate change directly affects the efficiency of several renewable energy sources (Bento, 2024; Bitencourt, 2024; Scianni et al., 2013). On September 19th 2024, in Rio de Janeiro, the Electric Sector Monitoring Committee (CMSE) convened representatives from key agencies, including the Ministry of Mines and Energy, the National Electric Energy Agency (ANEEL), the National Agency of Petroleum (ANP), the Electric Energy Trading Chamber (CCEE), and the Energy Research Company (EPE), as well as technicians from the National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) and the National System Operator (ONS). The meeting aimed to discuss, among other topics, the possible reintroduction of daylight-saving time, in response to the country's ongoing energy generation crisis. The measure was proposed by ONS, which reported difficulties in meeting the growing demand for electricity (Andrade, 2024; Bitencourt, 2024; Rodrigues, 2024; Steil, 2024).

According to CEMADEN, rainfall measurements since 1950 indicate that Brazil is experiencing one of the driest periods in its recent history: the Northeast semi-arid zone has faced recurrent droughts, with areas receiving 100–400 mm less rainfall per year than the historical average (Marengo et al., 2018); model projections indicate that the Amazon basin could experience an increase in dry season length by up to 69% and a reduction in rainfall by 44% relative to the control run, under scenarios of deforestation and climate change (Bottino et al., 2024). . As a result, the generation capacity of hydroelectric plants has been reduced, forcing the country to turn to alternative sources (Steil, 2024). Additionally, due to the unpredictability of wind patterns, ONS states that it is not feasible to fully rely on wind energy to meet demand (Bitencourt, 2024). Consequently, Brazil has increased its reliance on thermoelectric plants, raising emissions by ~9% and increasing energy costs for consumers (Andrade, 2024; Bitencourt, 2024; Rodrigues, 2024).

The proposed return of daylight-saving time aims to mitigate the effects of the so-called "ramp effect," a period of peak energy demand between 6 p.m. and 7 p.m. (Andrade, 2024). During this window, almost the entire thermoelectric system is activated, which, according to the Minister of Mines and Energy, Alexandre Silveira, directly influences final costs for consumers. The reinstatement of daylight-saving time could relieve pressure on the National Interconnected System (SIN) by extending solar energy production and reducing reliance on thermoelectric plants, while also encouraging the use of natural light, decreasing the need for electric appliances (Bitencourt, 2024).

According to ONS, adopting daylight saving time could reduce peak electricity demand in Brazil by up to 2.9% (Andrade, 2024). Moreover, thermoelectric plants not only pollute the environment but also raise the marginal cost of operation (CMO) to

R$1.248/MWh (US$224.14/MWh), whereas the cost before their activation was below R$500/MWh (US$89.80/MWh) (Bitencourt, 2024). ONS estimates that reinstating daylight-saving time could generate savings of up to R$400 million (approximately US$71.8 million) between October 2024 and February 2025, benefiting both the government and the population by lessening the impact of electricity cost increases (Andrade, 2024).

These challenges are directly related to our project and to the United Nations' 2030 Agenda, particularly Sustainable Development Goal (SDG) 7, which aims to ensure universal access to reliable and modern energy services, increase the share of renewable energy in the global energy matrix, and promote international cooperation in clean technologies (United Nations Brazil, 2024).

In response to this scenario, we developed an electrical energy monitoring system capable of analyzing real-time data and identifying waste. By enabling industries, businesses, and households to monitor their energy consumption, the project promotes financial savings while helping to mitigate the "ramp effect." Additionally, it contributes to environmental preservation by fostering awareness regarding the efficient use of energy resources (Rovere, 2016).

The system utilizes the non-invasive (no interference in the electrical grid) current sensor SCT-013 that measures the magnetic field variation around a conductive wire and converts this data into a current proportional to the original. This current is then transformed into signals that can be processed by an Arduino microcontroller, which interprets the readings. The data is subsequently transmitted over a network, where the Arduino communicates with an ESP32 - a more advanced microcontroller with higher processing capacity. The data can be accessed via a real-time application from anywhere in the world, enabled by the MQTT (Message Queuing Telemetry Transport) protocol, which ensures efficient data transmission to an external server (Sasaki, 2019; Silva et al., 2021). MQTT is crucial to our project, as it enables fast and reliable communication between devices: the ESP32 publishes the collected data to the server, and connected devices can subscribe to topics to receive this information in real time (Sasaki & Yokotani, 2019; Silva et al., 2021). Designed to optimize bandwidth use and reduce power consumption, MQTT is ideal for Internet of Things (IoT) applications like ours, where efficiency and reliability are essential (Sasaki & Yokotani., 2019; Silva et al., 2021). By focusing on real-time waste identification, the system empowers users to make immediate and informed decisions, optimizing energy use in a practical and accessible manner (Pfeifer, 2018; Rovere 2016; Tamkittikhum et al., 2015; Thakare et al., 2016).

Internationally, several consumer-oriented monitoring systems are well established. In the United States, smart plugs and IoT platforms such as Sense Energy Monitor and Emporia Vue provide detailed household consumption data via Wi-Fi and cloud analytics. In Germany, energy cooperatives use LoRaWAN-based smart meters for neighborhood-level monitoring, enabling collective management of distributed renewable generation. These examples show that energy monitoring is common in countries with advanced smart grids, but such infrastructure is limited in Brazil, where most households lack access to low-cost real-time monitoring. Developing affordable and reproducible prototypes adapted to the Brazilian scenario is therefore both relevant and necessary.

Unlike these commercial or proprietary systems, the proposed prototype emphasizes accessibility and transparency while maintaining technical rigor. It employs open-source hardware and software, enabling full replication and modification by students, technicians, and researchers, thereby bridging the gap between academic learning and practical energy management. Furthermore, built with low-cost and widely available components - such as the SCT-013 split-core current transformer, Arduino, and ESP32 - the system can be installed without electrical intervention or specialized labor, ensuring safety and ease of use. The data visualization through the MQTT protocol and multiple display formats such as LCD panels and web-based interfaces evince the accessibility of the project. Designed with the Brazilian energy context in mind - particularly the "ramp effect" and reliance on hydropower - the project promotes awareness and control over electricity consumption. By adopting a non-invasive approach, it achieves measurement reliability comparable to commercial systems at a fraction of the cost, offering a socially inclusive solution aligned with the United Nations' 2030 Agenda for Sustainable Development.

Literature Review

Theorical Foundation

The prototype relies on fundamental principles of electricity and magnetism, particularly Ohm's Law and Faraday's Law of electromagnetic induction. According to Ohm's Law, the relation between voltage V, current *i*, and resistance R is V = i R, forming the basis for quantifying current flow in a resistive circuit. Likewise, Ampère's Law states that an electric current produces a magnetic field *B* around the conductor, which decreases with distance r as $B = \mu_0 I / 2\pi r$.

When this magnetic field varies over time, Faraday's Law predicts an induced electromotive force (EMF):

$$E = -\frac{d\Phi_B}{dt}$$

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

where Φ_B is the magnetic flux. In practice, this means that a conductor carrying AC current generates a time-varying magnetic field that can be detected without direct electrical contact.

(Sanket et al., 2016; Miron-Alexe, 2016) Non-invasive current sensors, such as the SCT-013 transformer used in this work, exploit this principle: the alternating magnetic field around a single-phase conductor induces a proportional voltage in the sensor's coil. This voltage, after conditioning through a burden resistor and analog-to-digital conversion, allows real-time current estimation while maintaining electrical isolation and safety.

SCT-013 Current Sensor

The SCT-013 structure consists of a split-core coil, that precisely captures variations in the magnetic field when alternating current (AC) passes through the conductor. These variations induce a proportional current inside the sensor, as seen in Figure 01, which is used to determine the current flowing through the main conductor.

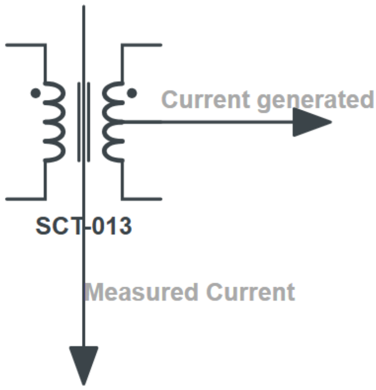

Figure 01 – Diagram illustrating the measured current and the generated current.
Source – AUTHORS

To read the current collected from the sensor, it is necessary to integrate it with an Arduino - a microcontroller that converts the data for reading. The SCT-013 sensor outputs an AC current signal that oscillates around zero, including negative voltages, which can be shown in Figure 02 (Sanket et al., 2016; Miron-Alexe, 2016). However, since the Arduino can only read positive voltages (0-5V) on its analog input, the signal must be shifted upward (Sanket et al., 2016; Miron-Alexe, 2016).

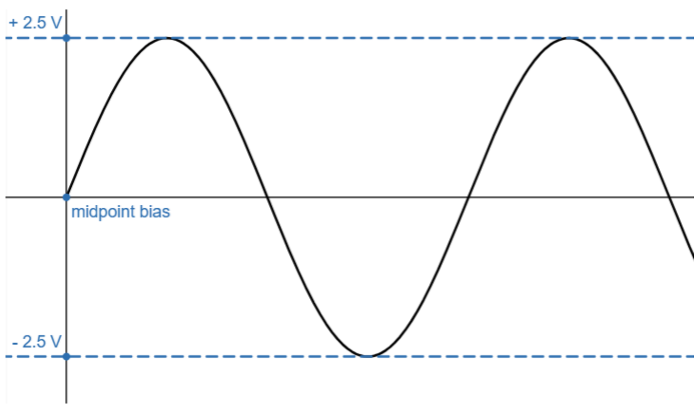

Figure 02 – Alternating current graph (-2.5V to +2.5V).
Source – AUTHORS

(Thakare, 2016; Miron-Alexe, 2016) To accomplish this shift, a voltage divider circuit is used, which is seen in Figure 04. It shifts the midpoint bias voltage to 2.5V. The sensor's AC voltage is then superimposed on this bias point, resulting in a waveform that oscillates around 2.5V - staying entirely within the Arduino's 0-5V range, as seen in Figure 03. This allows the full waveform, including what was originally negative, to be read accurately.

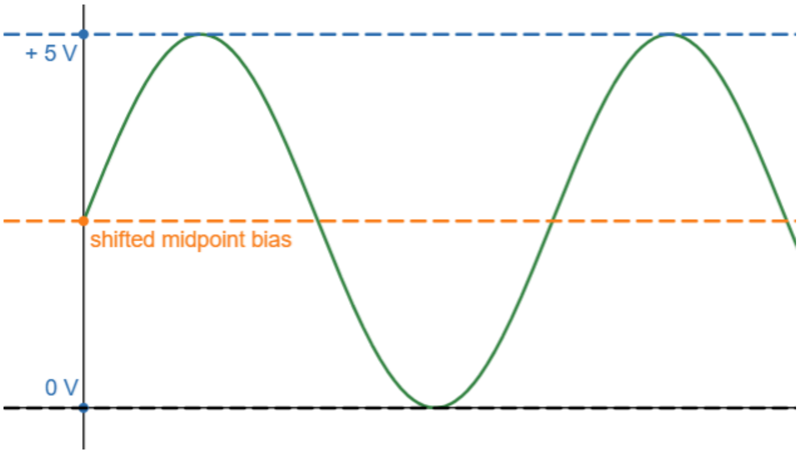

Figure 03 – Alternating current graph (0V to +5V).
Source – AUTHORS

The signal conditioning circuit consists of:

- A 100μF electrolytic capacitor, which filters and stabilizes the bias voltage.
- Two 10kΩ resistors forming the voltage divider.
- A 33Ω burden resistor, which converts the current output from the SCT-013 into a proportional voltage.

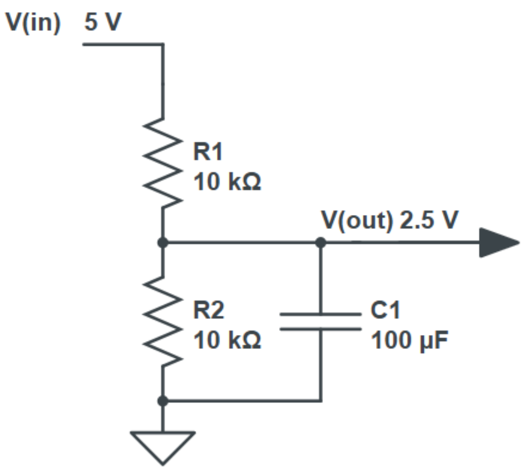

Figure 04 – Voltage divider scheme.
Source – AUTHORS

However, before connecting the signal to the voltage divider, it is essential to add the load (burden) resistor directly across the SCT-013 output terminals, as seen in the electrical diagram of Figure 05. This is necessary because the SCT-013 outputs current, not voltage - and a resistor is required to convert that current into a measurable voltage.

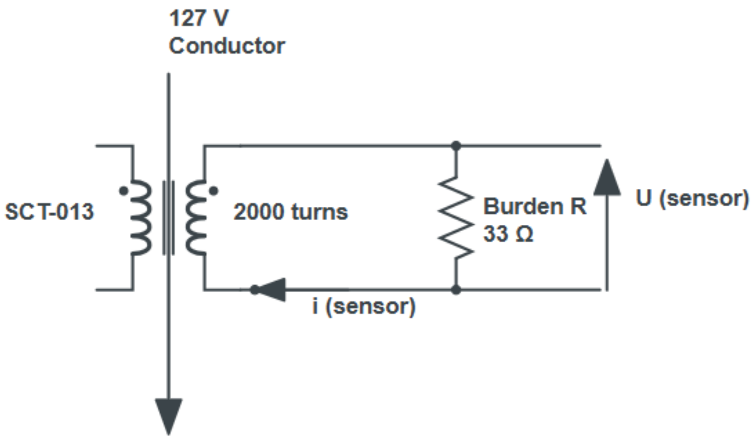

Figure 05 - Electrical diagram of the SCT-013 sensor in parallel with the calibration resistor.
Source – AUTHORS

To ensure the resulting voltage signal remains within the Arduino's 0-5V analog input range after biasing, the peak output voltage should not exceed ±2.5V.

$$R = V\ (\text{analog input} / 2) / I\ (\text{sensor}) = 2{,}5\ V / 0{,}0707\ A = 35{,}4\ \Omega.$$

The resistance, which we calculate multiple times further, is calculated using the first expression of Ohm's Law.

As the calculated value for the resistor does not exist in the market, we selected a load resistor of 33 Ω, the closest resistor value available.

The final result is a voltage waveform that remains entirely positive (0–5V) and proportional to the current in the wire, ready to be read by the Arduino's analog input.

The complete electric circuit is configured as illustrated in Figure 06.

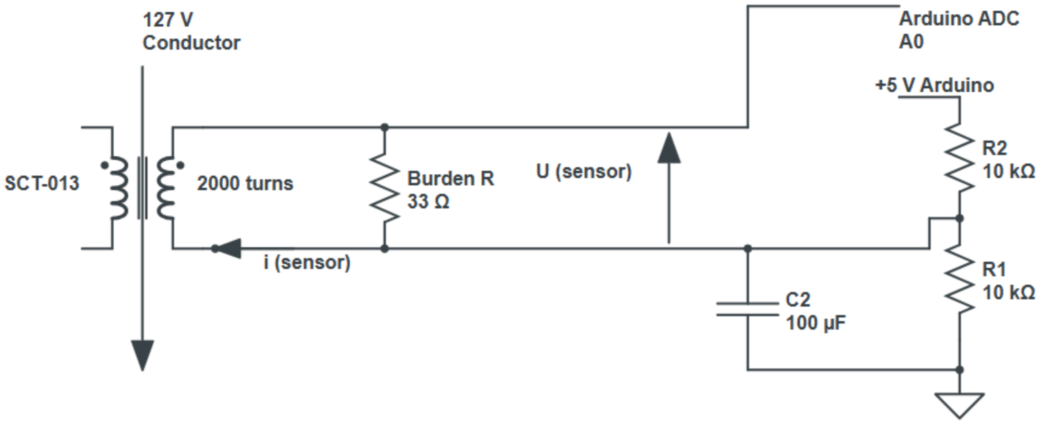

Figure 06 – Final Electric circuit
Source – AUTHORS

For the measurements, it is necessary to program the Arduino to perform the conversion.

The Arduino's serial communication is initialized with 9600 (baud rate), which refers to the number of bits transmitted or received per second.

The EmonLib library is responsible for performing the necessary conversion calculations. To do this, the current sensor must be initialized with a calibration value based on the resistor configuration used.

R = V (analog input / 2) / I (sensor) = 2.5 V / 0.0707 A = 35.4 Ω (closest resistor value in the market: 33 Ω)

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 33
CalibrationValue = 60.606

The line code to initialize with the corresponding calibration value is

```
SCT013.current(pinSCT, 60.606);
```

It is important to note that this calibration value is used with Arduino, which has a 5V analog input.

The entire code to print data at Serial Monitor is available in the github repository: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Arduino_test_Serial_print_example

The sensor must strictly be connected to only one of the wires of the measured conductor (either phase or neutral). If both the phase and neutral wires pass together through the sensor, the current will flow through one wire in one direction and return through the other in the opposite direction, generating opposing magnetic fields that cancel each other out. In this case, the meter will register zero current, making it impossible to perform the measurement.

Arduino and ESP32 Synchronization

The initial objective of the project was to avoid using Arduino and instead rely solely on the ESP32, a microcontroller with greater processing power and a wider range of features. This choice was made to enable the integration of the system with a data analysis interface, allowing users to monitor their electricity consumption at any time and from anywhere in the world.

(Maier et al., 2017) Advantages of integrating the ESP32 into the project:

- **High Processing Capacity:** The ESP32 features a dual-core processor with speeds up to 240 MHz, enabling rapid processing of large volumes of data collected by the current sensor.

- **Built-in Wi-Fi and Bluetooth Connectivity:** Integrated Wi-Fi allows the ESP32 to connect to local networks or the internet, facilitating data transmission to external servers and applications. Bluetooth functionality enables communication with nearby mobile devices, allowing quick configuration and local data transfer when necessary.

- **Compatibility with the MQTT Protocol:** The ESP32 supports the MQTT protocol, which is highly efficient for data transmission in IoT applications. MQTT allows lightweight and fast communication, essential for real-time energy consumption data transmission. This compatibility ensures the system can continuously and reliably send and receive data, minimizing delays and maximizing communication efficiency.

- **Expandable Storage and Memory Capacity:** With internal flash memory and support for expansion, the ESP32 can temporarily store large amounts of data in case of connection interruptions with the server, preventing the loss of important information.

The storage capacity allows the implementation of local algorithms for data pre-processing, reducing the amount of information sent to the cloud and saving bandwidth (Maier et al., 2017). To achieve the goal of using only the ESP32, we performed the necessary calculations to calibrate the load resistor in the circuit. As the ESP32 analog input voltage is just 3.3V, we made calculations with a different value than that of Arduino and with another voltage driver circuit.

R = V (analog input / 2) / I (sensor) = (1.65 V) / 0.0707 A = 23.33 Ω (closest resistor value in the market: 22 Ω).

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 22
CalibrationValue = 90.909

Therefore, the sensor initialization should include the newly calculated calibration value.

```
SCT013.current(pinSCT, 90.909);
```

To verify the accuracy of measurements using the ESP32, the collected data were compared to those obtained with a professional clamp ammeter. However, the results were unsatisfactory, as the ESP32 readings were dramatically off compared to the reference values. The reason for such discrepancy is discussed in session Limitations. Hence, the final measurement chain employs the Arduino for analog sampling and conversion, with the ESP32 dedicated exclusively to wireless serial communication via UART. This approach allows the ESP32 to manage the network and, consequently, provide remote access for users to view the measured data.

Serial Communication

To achieve the Arduino and ESP32 synchronization, UART (Universal Asynchronous Receiver/Transmitter) digital communication method is employed, which allows data exchange between two devices. (Gupta et al., 2020)

(Gupta et al., 2020) Main Characteristics:

1. **Asynchronous:** It does not require a shared synchronization clock between devices. Instead, data is transmitted with fixed format and baud rate, and the receiver must recognize and interpret the timing based on these parameters.

2. **Data Transmission:** Data is transmitted bit by bit in sequence. This can be done in two ways:
    - **TX** (Transmission): The device **sends** data.
    - **RX** (Reception): The device **receives** data.

(Gupta et al., 2020) Operation:

1. **Data Transmission:** The transmitter sends a data byte preceded by a start bit and followed by stop bits. The data byte is sent bit by bit, starting with the least significant bit.

2. **Data Reception:** The receiver waits for the start bit, then collects the data bits and stop bits to reconstruct the original byte.

To establish serial communication, SoftwareSerial library is added, through which we set the RX and TX pins, corresponding respectively to the Receiver and Transmitter.

```
SoftwareSerial serialBT(2,3);// RX(Arduino)-3 e TX(Arduino)-2
```

Now, the Arduino's serial initialization is performed, and its data transmission speed is set to 9600 bits per second:

```
serialBT.begin(9600);
```

To transmit collected data to the ESP32, UART print command is set.

```
serialBT.print(current);
```

However, in order to the ESP32 receive the data, it is initiated two separate serial communications: one to receive data from the Arduino (Serial2.begin), and another to send data to the computer (Serial.begin) for viewing via the Arduino IDE's serial monitor.

```
Serial.begin(9600); // Initializes serial communication with the computer's serial monitor at a baud rate of 9600.
Serial2.begin(9600, SERIAL_8N1, 18, 5); // RX(ESP32)-D18 and TX(ESP32)-D5
```

Subsequently, a standard program is implemented to receive data sent by the Arduino and received by the ESP32, adjusted with our own variables.

The code is detailed in the github repository: https://github.com/Peagudoo/Monitoring-Project-Code/blob/b978bf0b2189e62114fa00f6bf7182c91115bbd6/ESP32_RecieveData-FromArduino_example

Thus, the connection between the Arduino and ESP32 was established. To make the data stored in the memory of both microcontrollers available in a user-friendly interface, the MQTT protocol is implemented, which is responsible for storing data on an external server connected to the network. Accordingly, the ESP32 transmits the data to the network, and an application collects these data on its interface, allowing the user to access information about their electricity consumption.

MQTT Protocol

(Sasaki & Yokotani, 2019; Silva et al., 2021) The MQTT protocol establishes communication between client and server, where the client can both store and receive data. This is achieved through a Publish-Subscribe method, which involves a Broker - an intermediary information server that receives data sent from sensors, manages it, and shares it according to the client's needs, as could be seen in Figure 07.

The client acts in two distinct roles: as a Publisher (posting data) and as a Subscriber (receiving data). The relationship between the client and the Broker functions such that the Broker organizes received information in a hierarchical system according to topics. Clients can subscribe to the topics they wish to receive; however, the Broker manages the requests, so the Client and Publisher do not communicate directly, thereby maintaining anonymity for both parties. (Sasaki & Yokotani, 2019; Silva et al., 2021)

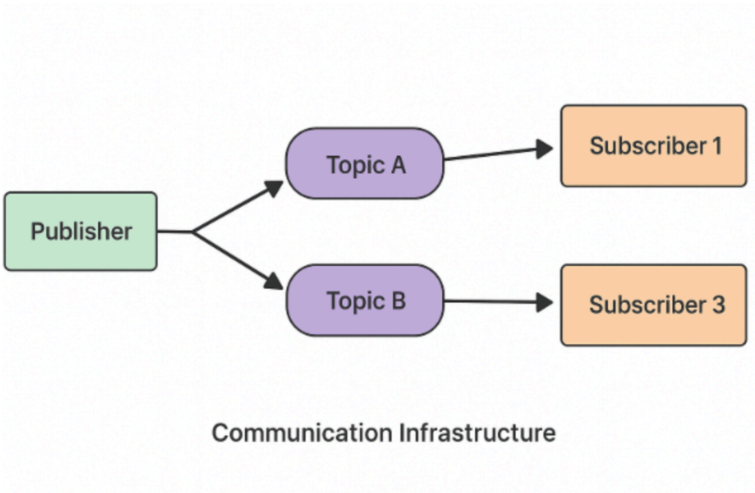

Figure 07 – Communication diagram using the MQTT protocol.
Source - AUTHORS

In the project, the following topics are used: electric current, energy, cost, and power, with each item representing a specific topic. The Publisher is the ESP32, which, upon receiving data collected from the Arduino, sends it to the Broker. The client is the application, which requests data from the Broker, and the Broker in turn delivers the data.

Advantages of the MQTT Protocol:

- Low memory consumption.
- Low processing requirements.
- Low bandwidth usage.
- Low latency.
- High reliability.

(Sasaki & Yokotani, 2019; Silva et al., 2021)

Since the Publisher does not send information directly to clients, it does not need to store client information or send multiple copies of data - only the specific data requested. Additionally, only information related to the Broker, its topics, and packet transmissions is stored. For these reasons, MQTT is excellent for IoT applications, providing a low-cost and accessible solution for projects handling moderate amounts of data. (Sasaki & Yokotani, 2019; Silva et al., 2021)

Beyond these well-known benefits, recent evaluations confirm MQTT's scalability in large deployments. For example, Silva et al. (2021) demonstrated that MQTT brokers can handle up to 500 simultaneous clients publishing in parallel while maintaining latency below 200 ms per message, with stable throughput of several thousand messages per second. Under broker load tests with Mosquitto (a lightweight, open-source MQTT broker widely used for IoT applications) and EMQX (a high-performance, enterprise-grade MQTT broker), the system sustained low packet loss and CPU usage below 70%, even during peak conditions. Furthermore, MQTT supports reliable Over-the-Air (OTA) firmware updates - that is, the remote distribution and installation of new firmware onto devices without physical access - exceeding 100 KB with more than 99% success rate when QoS (Quality of Service) levels 1 or 2 were enabled (Silva et al., 2021). QoS 1 guarantees that a message is delivered at least once, while QoS 2 ensures it is delivered exactly once, providing stronger reliability in critical applications (Silva et al., 2021). These results reinforce that MQTT is not only suitable for small-scale prototypes such as ours, but also inherently capable of scaling to multi-device and multi-channel energy monitoring systems, maintaining efficiency, low latency, and reliability in scenarios ranging from household deployments to large smart grid infrastructures (Silva et al., 2021).

Methodology

Prototype Development

The prototype was developed to emulate a typical single-phase electrical installation, enabling the monitoring of both total and individual circuit consumption. The experimental setup consists of four circuit breakers: one main breaker that supplies the entire system - allowing total energy measurement through a single non-invasive SCT-013 sensor - and three auxiliary breakers dedicated to specific electric devices, as seen in Figure 08. This configuration simulates residential or small commercial environments in which users can analyze consumption at multiple points.

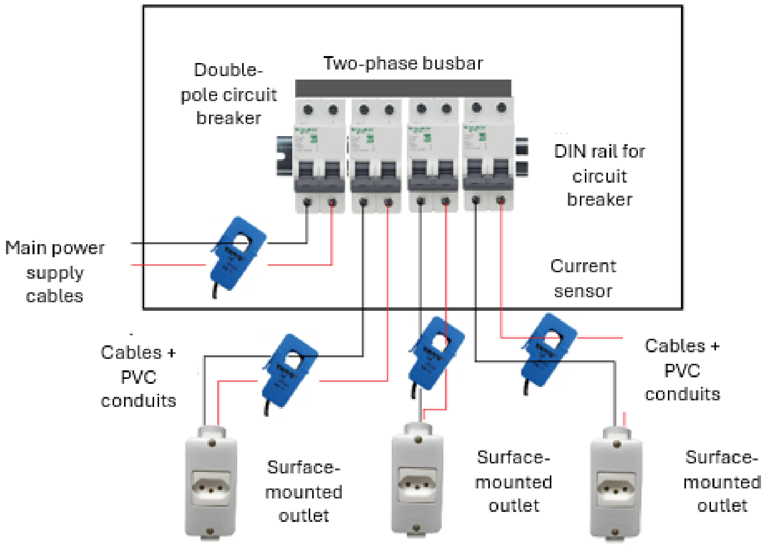

Figure 08 – Initial sketch of the project.
Source – AUTHORS

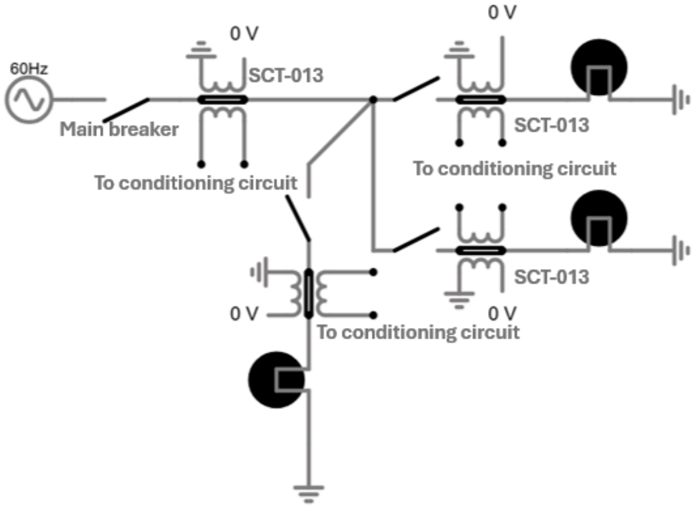

Figure 09 – System overview circuit diagram.
Source – AUTHORS

The components were mounted on a wooden panel containing a power box that houses the sensors, Arduino microcontroller, and ESP32 module. Each current sensor was clamped around the conductor of interest to ensure electrical isolation during measurement. Four LCD modules were incorporated to provide local visualization of instantaneous current data from each monitored circuit, as shown in Figure 10. The displays were mounted beside the corresponding outlets to create an intuitive interface for the user.

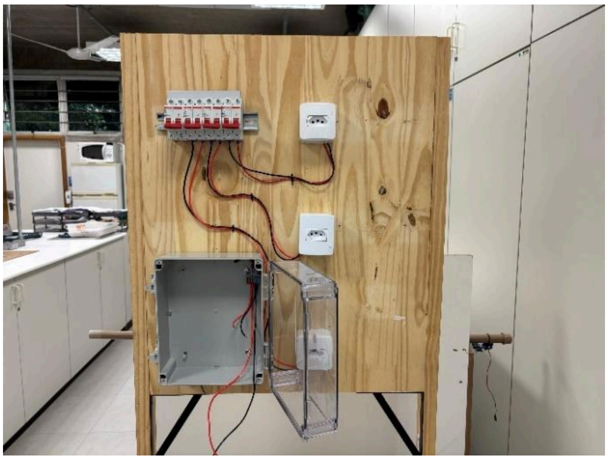

Figure 10 – Image of the wooden panel and the power box (left), as well as the display. LCD to display real-time readings (right).
Source – AUTHORS

The circuit is powered by a switched-mode power supply that converts 127 V AC mains input into a stable 12 V DC output. A voltage regulator limits this to approximately 6.5 V to protect the microcontrollers.

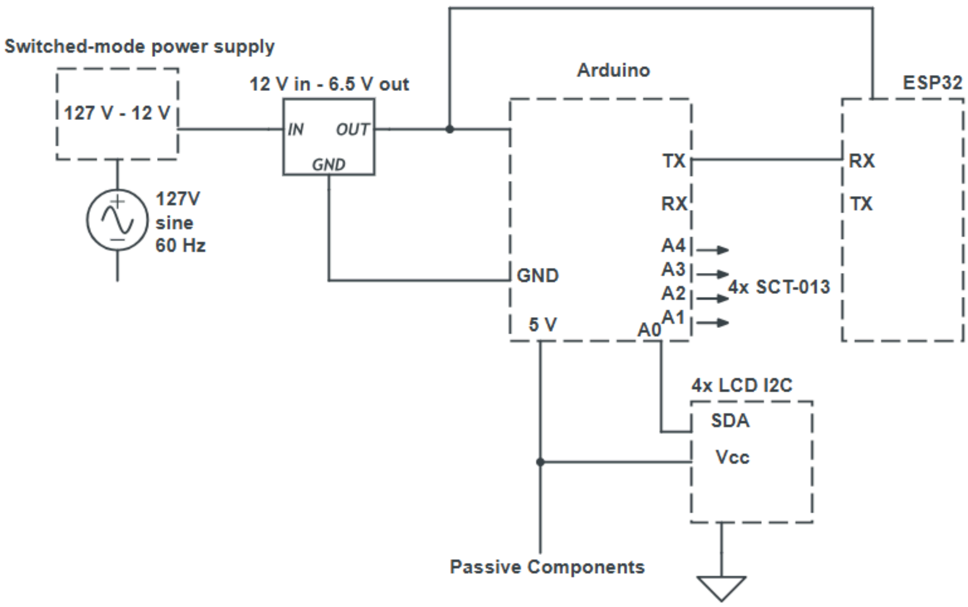

Figure 11 – Power and Communications circuit
Source – AUTHORS

The passive components - resistors, capacitors, and connectors - were assembled on a prototyping board, and together with the Arduino and ESP32 were enclosed within the power box for safety and organization, as seen in Figure 12. The circuit connections to the four non-invasive current sensors extend outside the power box, allowing for measurement of the electrical conductor wires.

It is important to note that, in this setup for panel creation, we intervened in the electrical circuit only for convenience, powering the microcontrollers directly from the main supply. However, in real-world applications, no electrical intervention is necessary, as the modules can be powered using portable batteries or USB adapters without struggle.

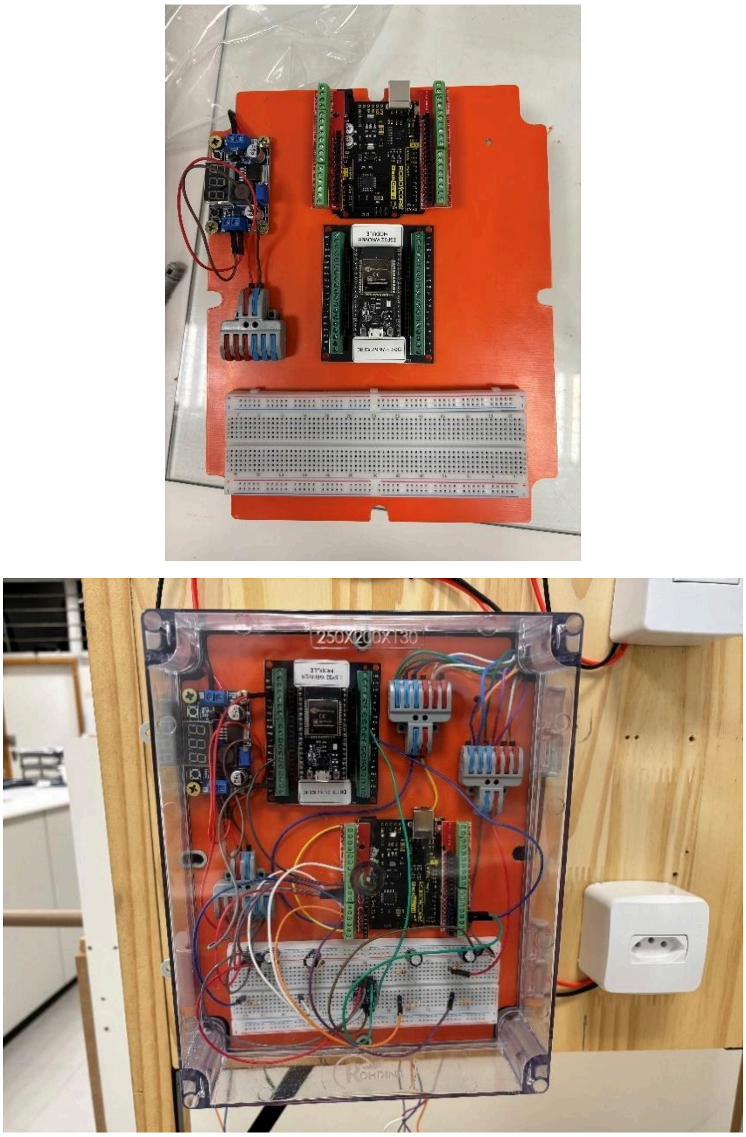

Figure 12 – Image of the electrical box, with its respective connections.
It is not possible to observe the current sensors and their connections in this image.
Source - AUTHORS

The final circuit configuration connects the main power line to the primary circuit breaker, which distributes the 127 V AC supply to three independent outlets corresponding to the monitored loads, as seen in Figure 08 and Figure 09. In parallel, the mains voltage feeds a switched-mode power supply that converts 127 V AC to 12 V DC. A subsequent voltage regulator limits the output to 6.5 V to ensure safe operation of the Arduino, ESP32, LCD displays (Figure 11), and signal-conditioning board (Figure 06).

System control is achieved through firmware developed for both microcontrollers. The Arduino handles analog signal acquisition from the SCT-013 current sensors, while the ESP32 manages data transmission and communication via the MQTT protocol. The complete source codes are available in the project's public repository.

Arduino:
https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Final_Arduino_code

ESP32:
https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Final_ESP32_code

Testing

The prototype performance was validated using three complementary visualization modes: (1) local LCD displays, (2) an MQTT-based mobile application, and (3) a web interface hosted on the ESP32. These approaches ensured both on-site and remote data verification.

LCD Display Testing

To verify measurement accuracy, sensor readings were compared against a calibrated clamp ammeter. Tests were performed under controlled load conditions including resistive devices such as lamps and soldering irons. The LCD interface, implemented via the LiquidCrystal_I2C library, displayed real-time data from the SCT-013 sensors, as seen in Figure 11.

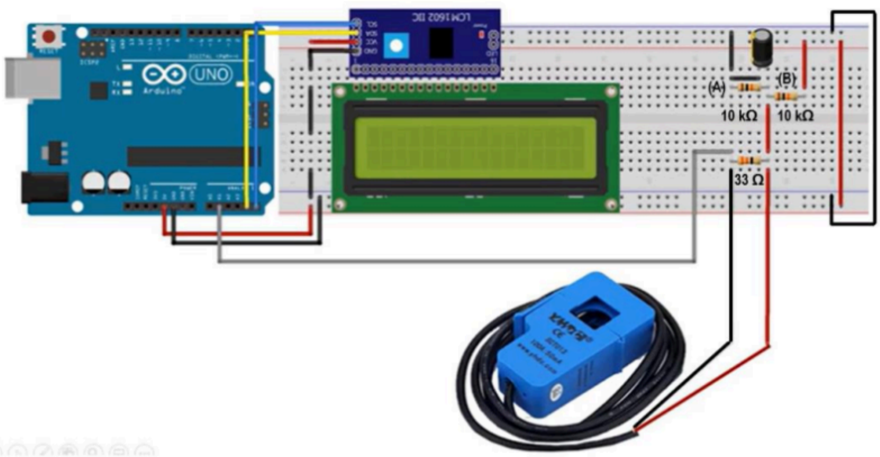

Figure 13 – Use of the LCD display to visualize data from the SCT-013.
Source – AUTHORS

Four 20x4 LCD modules were individually addressed to represent the four monitored circuits. The object declaration follows the standard format of the library:

```
LiquidCrystal_I2C lcd1(adress, n_collumns, n_rows); //object that controls the LCD display.
```

The parameters correspond respectively to the device address, number of columns, and number of rows. In this project, the following configuration was adopted:

```
LiquidCrystal_I2C lcd1(0x24,20,4);
LiquidCrystal_I2C lcd2(0x25,20,4);
LiquidCrystal_I2C lcd3(0x26,20,4);
LiquidCrystal_I2C lcd4(0x27,20,4);
```

Display initialization and backlight activation were executed with the commands:

```
lcd1.init();
lcd1.backlight();
```

Each LCD presented one variable per line, enabling direct observation of instantaneous current values. The complete code routine is available in the public repository:

https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/LCD_Display_Printing_Example

The initial tests aimed to analyze the error rate that the sensor could present compared to the clamp ammeter. For this purpose, it was used only one display, one sensor, and the electrical device being measured. At this specific testing stage, the Arduino and the ESP32 were not yet synchronized, as their communication was not necessary for the displays to function.

Test performed with a lamp:
Value measured by the SCT-013 sensor: 160 mA
Value measured by the clamp ammeter: 120 mA
Margin of error: 33%

Test performed with a soldering iron:
Value measured by the SCT-013 sensor: 160 mA
Value measured by the clamp ammeter: 120 mA
Margin of error: 33%

In Test 2, conducted with the soldering iron, it was observed that the sensor provided readings even when no current is present. We believe this may have occurred due to external interference generated by electronic devices present in the testing environment (laboratory).

This hypothesis arose because, when tested in other environments outside the range of these electronic devices - such as at home - the sensor provided zero current readings when not measuring and the margin of error reduced drastically. Therefore, it is probable that the magnetic field from other electronic devices induced a response in the sensor, resulting in readings even though they were not from the conductor wire.

Application Testing using the MQTT Protocol

Once the synchronization between the Arduino and the ESP32 was completed, and the latter integrated with the MQTT protocol, testing with the application became possible. As mentioned earlier, the integration of the protocol enables remote monitoring of energy consumption from anywhere in the world at any desired time (Sasaki & Yokotani, 2019; Silva et al., 2021)

For this purpose, the developed system uses an iOS application called ON OFF, which allows the capture of data published on the external MQTT server. Thus, the application acts as the Client, while the ESP32 functions as the Publisher.

The team decided that only data from the main circuit breaker (which measures the total electrical current of the establishment) would be displayed in the application during testing.

This link contains an MQTT video test: https://docs.google.com/presentation/d/1d3qZIVl55eJ1PHWbBPnyKwMF6CbK8FIfDjc_fjMUi6Q/edit?usp=sharing

Web Interface Testing

A web server was implemented on the ESP32 so that consumption data can be accessed remotely via a standard HTTP interface. This allows users to monitor energy usage in real time from any browser on the network.

The code is available at the following github repository: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/WebServer_test_code

Test video with the web server: https://docs.google.com/presentation/d/1n3twGLn_ofM23tX9RS8k1i5nGzYXelZxA8VGZgHaPw0/edit?usp=sharing

Results

An analysis of the margin of error for various electrical appliances was conducted and then compiled into Table 1. Additionally, a comparative graph between the non-invasive current sensor and the clamp ammeter was created, as shown in Figure 12, and a correlation plot in Figure 13, illustrating how the measurement error varies with the current measured by the SCT-013.

Nº	Devices	SCT-013 (A)	Professional clamp ammeter (A)	Deviation	Margin of Error	N (measurements taken)	SD (A)
1	Sterilair Air Purifier	0.26	0.25	0.01	4%	5	0.009
2	LG SmartTV	0.62	0.65	-0.02	-5%	5	0.012
3	Arno Fan (low power)	0.64	0.65	-0.01	-2%	5	0.011
4	Arno Fan (medium power)	0.82	0.82	0.00	0%	5	0.012
5	Arno Fan (high power)	1.07	1.08	-0.01	-1%	5	0.013
6	Blender (low power)	1.44	1.46	-0.02	-1%	5	0.015
7	Consul Refrigerator	1.60	1.63	-0.03	-2%	5	0.016
8	Blender (high power)	1.74	1.75	-0.01	-1%	5	0.016
9	Philco Vacuum cleaner	3.32	3.33	-0.01	0%	5	0.021
10	Conair Hair Dryer (low power)	3.45	3.50	-0.05	-1%	5	0.020
11	Philco Hair Dryer (high power)	4.35	4.38	-0.03	-1%	5	0.020
12	Conair Hair Dryer (high power)	6.22	6.30	-0.08	-1%	5	0.021
13	Philco Hair Dryer (high power)	8.20	8.40	-0.20	-2%	5	0.022
14	Cadence Electric Kettle	8.31	8.46	-0.15	-2%	5	0.022
15	Microwave Oven	12.14	12.70	-0.56	-4%	5	0.025

Table 01 – Comparative table with data collected from SCT-013 and professional clamp ammeter.

Source - AUTHORS

The average margin of error is at most ±5%.

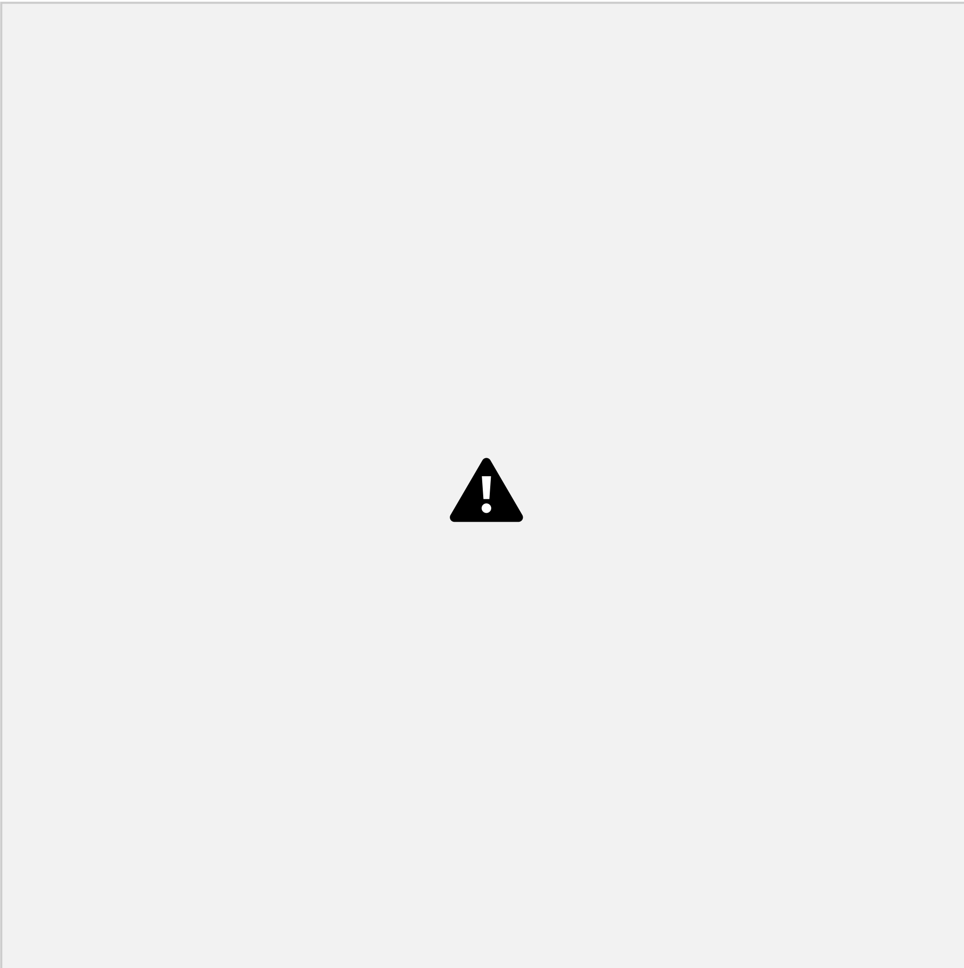

Figure 12 – Comparative graph between data read by the SCT-013 sensor and the professional clamp ammeter.

Source - AUTHORS

As summarized in Table 1 and Figure 15, the SCT-013 readings agreed with the reference meter within ±5% for all tested appliances. The average error was around 1–2%, with small standard deviations, indicating consistent performance. These results confirm that the SCT-013 provides sufficient accuracy for low-cost monitoring applications.

To ensure statistical validity, each measurement was repeated five times (N = 5) for each tested load. The SCT-013 showed high repeatability, with standard deviations typically below 0.025 A. The table reports both the mean error relative to the clamp ammeter and the corresponding standard deviation across repetitions.

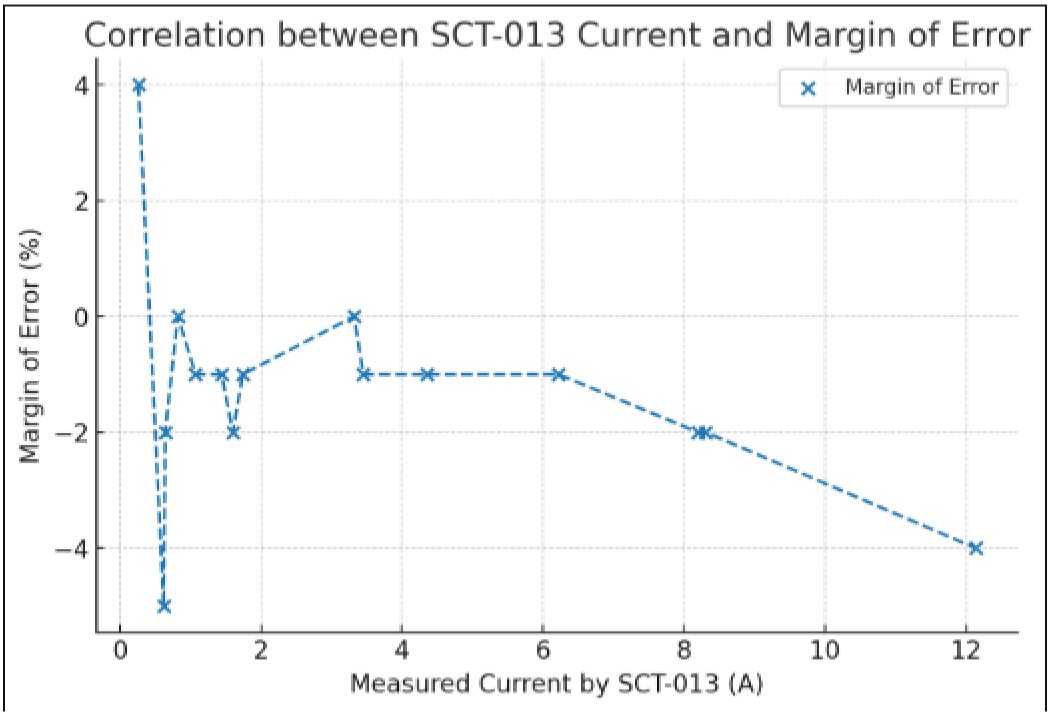

Figure 13 – Correlation graph between measured current and margin of error.
Source - AUTHORS

Figure 16 demonstrates that at low currents the relative error is high compared to medium currents (2 - 6 A). This phenomenon is consistent with the sensor's fixed offset and the ADC quantization effect (explained in the next session).

Uncertainty Budget

The accuracy of the measurements obtained with the prototype depends on the combined performance of the sensing element, conditioning circuit, and analog-to-digital conversion stage. To assess the system's reliability, an uncertainty budget was established based on repeated laboratory tests under controlled environmental conditions. The main uncertainty contributors identified were the burden resistor characteristics, the ADC performance of the microcontroller, and the linearity of the SCT-013 current transformer.

Temperature Drift of the Burden Resistor

To characterize additional effects not included in the initial estimate, supplementary experiments were conducted to evaluate thermal drift of the burden resistor. During operation, the 33 Ω resistor dissipated approximately 0.165 W at nominal load (secondary current 70.7 mA), leading to an average temperature rise of 17 °C after 15 minutes of continuous use. Resistance increased by 0.09 Ω (0.27%), consistent with theoretical predictions for a metal-film resistor with a 50 ppm $°C^{-1}$ temperature coefficient. Under an overload condition corresponding to double the nominal current, the power dissipation reached 0.66 W and the temperature rose by 35 °C, resulting in a resistance variation of 0.19 Ω (0.58%).

Although this drift produces only minor deviations in the measured current, it represents a relevant contribution to the overall uncertainty, particularly under sustained or high-load operation. For the present prototype, the temperature-related contribution is estimated at ±0.3% under normal conditions and up to ±0.6% under overload. These results demonstrate that thermal effects remain small compared with the dominant linearity and tolerance components but are measurable and should be included in future calibration analyses.

ADC Non-linearity and Combined Effects

(Adamo et al., 2007; Zhengbing et al., 2015) The analog-to-digital conversion represents an additional source of systematic uncertainty. The Arduino's 10-bit ADC (ATmega328P) converts analog voltages into discrete digital steps of approximately 4.88 mV per level, known as the Least Significant Bit (LSB). Its Integral Non-Linearity (INL) - the deviation between the actual and ideal conversion curve - is approximately ±2 LSB, according to the manufacturer's datasheet. The ESP32, responsible for wireless data transmission, employs a 12-bit ADC with an INL of up to ±12 LSB depending on the channel. Experimental evaluation using a calibrated 1.000 V RMS sine wave revealed deviations of ±0.4% for the Arduino and ±0.7% for the ESP32, values consistent with these specifications.

Because the Arduino is responsible for primary signal acquisition, a conservative ±0.5% ADC uncertainty was incorporated into the budget. Temperature drift and ADC non-linearity can interact, since a small rise in burden resistor voltage increases the analog input level, slightly amplifying non-linear distortion at higher ADC codes.

Combined Uncertainty and Outlook

The burden resistor (33 Ω, ±5% tolerance) and the voltage divider resistors (10 kΩ, ±1% tolerance) introduce a proportional scaling uncertainty. The Arduino ADC, with 10-bit resolution (≈4.88 mV/step over 5 V) and a typical nonlinearity of ±0.5 LSB (ATmega328P), adds quantization and transfer-curve error (Adamo et al., 2007; Zhengbing et al., 2015). The SCT-013 datasheet specifies linearity deviations up to ±3% across its nominal range. Using the root-sum-square (RSS) method, the combined type-B uncertainty is estimated at 6%, which aligns with the maximum experimental deviation observed (5%). Random errors, evaluated through repeated measurements, were comparatively small (standard deviation <0.02 A in most cases).

$$u_c = \sqrt{(5.0\%)^2 + (1.0\%)^2 + (1.0\%)^2 + (3.0\%)^2 + (0.5\%)^2 + (0.3\%)^2} = 6.02\%$$

Hence, these factors may influence accuracy in long-duration or high-temperature environments and are identified as priorities for future investigation.

Project Costs

A cost analysis of the project was conducted for potential commercial application, as seen in Table 02, and we noted that the total cost differs from that of developing the prototype. It is important to consider that the shopping was made in Brazil, and the total cost may vary for different countries.

Installation Type	Total Cost (R$)	Total Cost (US$)	Notes
User's commercial installation	R$ 223.47	US$ 40.14	Cost of the installation used by the user.
Experimental Panel for testing	R$ 579.93	US$ 104.15	Constructed by the research team to simulate a house electrical panel for experiments.

Table 02 – Complete project cost table.
Source – AUTHORS

Limitations

As mentioned previously, the initial goal of the project was to use only the ESP32 to convert the data collected by the sensor and provide it on the network via MQTT.

However, despite performing the necessary calculations to configure the load resistor, the collected data were not sufficiently accurate.

R = V (analog input / 2) / I (sensor) = 1.65 V / 0.0707 A = 23.33 Ω.
The closest commercially available resistor to the calculated value is 22 Ω.

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 22
CalibrationValue = 90.909

Therefore, the sensor initialization should include the newly calculated calibration value.

```
SCT013.current(pinSCT, 90.909);
```

Even with the correct calibration values and burden resistor configuration, we obtained inaccurate measurements when using the ESP32 alone. Measured values were off by more than 50%, and data was collected even without current passing through the SCT-013.

This discrepancy is attributed to the characteristics of its internal analog-to-digital converter (ADC), which is not well suited for low-level, biased analog signals such as those produced by the SCT-013. The ESP32 ADC typically exhibits a voltage offset of approximately 0.17 V, meaning that conversions do not start at 0 V even in the absence of input (Maier et al., 2017). In addition, the ADC suffers from integral nonlinearity, channel-dependent gain variation, and sensitivity to input impedance and stability (Adamo et al., 2007; Zhengbing et al., 2015). The SCT-013 output, after passing through the burden resistor and midpoint bias network, has relatively high impedance, which can lead to unstable sampling when directly connected to the ESP32. Small bias fluctuations can cause the ADC reference node to drift, leading to noisy or inconsistent readings, and a single calibration constant becomes unreliable across different load levels. In contrast, the Arduino's 10-bit ADC, though simpler, maintains a more linear and predictable transfer function over its input range, resulting in more stable and reproducible current measurements (Thakare et al., 2016). For these reasons we performed acquisition and analog processing on the Arduino (which exhibited more linear ADC behavior); after synchronizing the Arduino with the ESP32, the ESP32 receives the processed data and publishes it to the MQTT broker, from which the application subscribes to topics and acts as a client (Sasaki & Yokotani, 2019; Silva et al., 2021).

Another important factor to consider is that the external environment slightly affects the results collected by the sensor. For example, when the sensor is not measuring current from a conductor wire, it may pick up magnetic fields emitted by nearby electronic devices. However, when there is an active current flow in the conductor, the sensor ignores this external interference and measures only the data from the intended device.

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Conclusion

Project Conclusion

In general, the group concludes that the electric energy monitoring project successfully achieved its main objectives, demonstrating it to be an effective and accessible system capable of promoting awareness about energy consumption – the system has an accuracy of approximately 95%. By employing a non-invasive current sensor and technologies such as Arduino, ESP32, and the MQTT protocol, it became possible to monitor energy consumption in real time from anywhere with an internet connection, thereby helping to reduce waste and encouraging more responsible electricity use (Sasaki & Yokotani, 2019; Silva et al., 2021; Tamkittikhun et al., 2015; Thakare et al., 2016).

Furthermore, from a socio-economic perspective, the project holds great importance as it addresses a global issue: the efficiency in electrical energy use. By monitoring energy expenditure, users can identify major points of waste and adopt more effective measures to optimize consumption. In Brazil, where electricity costs can represent a significant burden on household budgets, especially for low-income families, this technology has the potential to generate a profound positive impact. Companies and other sectors that adopt this solution can also achieve greater energy efficiency, which translates into financial savings and enhances their market competitiveness (Bento, 2024; Emanoel, 2023).

However, like any project, our system has its advantages and drawbacks. Among its main advantages, accessibility stands out, as the project can be used by diverse audiences given that the materials employed have an affordable cost, evinced by Table 02. Additionally, safety is a strong point, since the use of the SCT-013 sensor avoids the need to directly interfere with electrical wiring, facilitating installation and eliminating the risk of electric shocks. Another important aspect is innovation, since the solution enables remote and real-time monitoring of energy consumption through the integration of the ESP32 with the MQTT protocol, allowing consumption tracking from anywhere in the world (Sasaki & Yokotani, 2019; Silva et al., 2021).

On the other hand, the project presents some drawbacks, such as dependence on a stable internet connection, since remote monitoring relies on a constant internet connection for data to be transmitted correctly. In locations with limited network infrastructure, the system's effectiveness may be compromised. Another shortcoming is the absence of an alert system, as the current system does not issue notifications when energy consumption exceeds certain thresholds. Moreover, the project did not implement cloud-based analysis, active response due to the high demand of energy, and multi-channel measurement which is highly recommended for applications in complex industrial systems.

Safety and Ethics

The system interfaces with dangerous mains voltage, so industry-standard safety measures are required. All high-voltage conductors are properly insulated and enclosed to prevent accidental contact. A suitably rated fuse is placed in series with each monitored conductor to protect against overloads. Clearance distances and insulation of materials comply with relevant electrical standards. The SCT-013 sensor provides galvanic isolation, but care is taken in circuit layout and wiring to maintain safety. On the ethical side, the device reports only aggregated energy use, not personal information, so privacy impact is minimal. Users should still be informed that their consumption data is collected and transmitted remotely, but no sensitive personal data (e.g. identities or usage patterns per person) are exposed. It is important to note that the SCT-013 must be clamped around just one single phase conductor, otherwise it reads opposed magnetic fields that cancel each other.

Future Implementations

For readers reproducing this work, we recommend either using the Arduino (or an external high-linearity ADC or op-amp buffer) for acquisition, or applying per-channel calibration tables and oversampling/averaging techniques on the ESP32 to compensate for its nonlinearity and shift its 0.17 V voltage offset. Finally, we intend to completely eliminate external interference caused by the electromagnetic congestion of electronic devices present in the environment by using a metallic shielding material to cover the current sensor relative to the external environment. This approach will enable measurement exclusively of the magnetic field generated by the conductor wire, thereby ensuring greater precision in the readings.

For future work, we suggest focusing on a few key enhancements: integrating an alert system for threshold-based notifications, adding cloud-based data storage and analysis for trend tracking, and exploring AI-driven energy management (Rovere, 2016). These improvements would streamline the system and provide more intelligent, proactive insights into energy use.

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The authors extend heartfelt thanks to the reviewer for the detailed and thoughtful critique, which provided both technical and conceptual insights that greatly strengthened this work. Your specific observations regarding the introduction's clarity, sensor methodology, and circuit design contributed to meaningful improvements in both structure and precision.
Your engagement with the technical aspects - particularly the discussion of non-invasiveness, burden resistor optimization, and data presentation - helped refine the paper's accuracy and scientific transparency. We truly appreciate the time and expertise invested in reviewing this manuscript.

The authors remain open to making further refinements or addressing additional minor points if the reviewers or editors consider them necessary for final publication.

Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

Overall comments: This is a generally well-written paper. The student addresses a timely and important subject. The student ties the relevance of their engineering project directly to a pressing problem. In order to supply a daily evening surge in power needs in Brazil polluting coal fired power plants need to be brought online. The author proposes instead reducing this demand through monitoring of where demand can be reduced using their device. The student engages with the literature to understand the broader problem and come to a first possible solution.

A weakness of this work is that there is no comparison or review of existing similar systems. I live in the UK and for some years we have a power monitoring device which shows us how much power we're using at any time, and the total cost. All these devices send data back to a base station. I think they use a mesh network. So each house connects to nodes in neighbouring houses. In this sense, such monitoring is not novel in the UK, though it might be unusual or uncommon in Brazil (I don't know).

If such devices are not common in Brazil then the paper should consider some review of what's common elsewhere (such as the UK). Why might their solution be better than what already exists? The difficulty with making the measurements directly with the ESP32 is a bit confusing for the reviewer.

I would recommend another round of review if all the comments, some major, some minor, can be addressed.

Specific Comments:

Introduction: Some text can be trimmed from the opening on the importance of electricity to society. Some extra details can be added which may be surprising to your readers not based in Brazil. Particularly relating to the change in weather patterns. You say rainfall is down, but being specific/precise adds value for the reader, this is what came up when I looked this up:

"Overall, Brazil has experienced a downward trend in average rainfall since around 1950. However, this trend is not uniform:

Northeast and other semi-arid areas are becoming drier.

Southern regions are seeing a recent uptick in rainfall.

Amazon is facing longer, more severe dry seasons and drought intensification. (20% less rainfall per decade)."

Thank you for this valuable suggestion. The opening paragraph of the introduction was condensed to avoid redundancy, and new quantitative details about rainfall trends across Brazil were incorporated using updated CEMADEN and ONS data. Specific regional differences (Northeast droughts, Amazon dry seasons, and Southern rainfall increase) were added in the third and fourth paragraphs of the Introduction.

The last paragraph of the introduction could be less verbose as it repears information mentioned previously.

I'm not sure it's appropriate to include the information from the heading "Electric Current" to "Magnetic Field". All of this could/should be summarised with a few labelled equations.

"Now that we have defi ned electric current, resistance, voltage, magnetic fi eld, and magnetic induction, it is possible to establish the foundation of the project." --- text can be removed.

The redundant material in the final paragraph of the Introduction was merged and restructured for conciseness. The theoretical background sections were shortened to a few labelled equations, with all redundant textbook-style explanations removed. The transition sentence about defining electrical quantities was deleted as recommended.

The author repeatedly mentions that their sensor method is "non-invasive". However, they are loading the other devices. Energy is being drawn from the main circuit. The biasing circuit is causing the "burden" resistor to constantly draw 70 mA.

The terminology “non-invasive” was clarified to emphasize that the SCT-013 sensor measures current magnetically without breaking the circuit. A paragraph was added in the Uncertainty Budget section explaining that although a small bias current flows through the burden resistor, this current is limited to low milliamperes and does not load the monitored circuit. Also, this current is the one generated through the induction of the SCT-013. The temperature drift influence was addressed analytically, and the effect was quantified as negligible under laboratory conditions.

Why not have a much larger "burden" resistor, reduce the current flow, and then divide down that voltage. How does the ambient temperature affect these measurements?

Increasing the burden resistor would indeed lower the secondary current, but it simultaneously raises the output voltage of the transformer in direct proportion. In practice, this approach does not improve efficiency or linearity - it simply shifts the same signal energy into a higher-voltage, lower-current form. The additional step of dividing down that voltage reintroduces resistive loading and noise, offering no real metrological advantage. Furthermore, excessive secondary voltage can cause the sensor’s magnetic core to approach saturation under high primary current, distorting the waveform and degrading phase accuracy. For this reason, a 33 Ω burden resistor was retained, as it ensures the signal remains within both the sensor’s linear operating range and the Arduino ADC’s 0-5 V input window.

"These values correspond to currents up to 100 A. Therefore, we selected a load resistor of 33 Ω, the closest resistor value in the market." --- Unclear

The explanation was rewritten in the Prototype Development section to clarify that the 33 Ω burden resistor was selected based on the SCT-013's rated secondary current and the desired voltage range compatible with the Arduino ADC input.

"However, our tests conducted with the ESP32 were unsatisfactory, as the measured values did not closely match the actual values. Conversely, tests performed with the Arduino yielded current measurements that were much closer to reality." -- There is no discussion here of the accuracy with which tests were made. What was used to measure/verify voltage? Why did the ESP32 results not match expectations?

A full paragraph was added in the **Testing** subsection describing the comparative procedure using a professional clamp ammeter for validation. The explanation now includes the reason for ESP32 deviations - its internal ADC offset (~0.17 V), input non-linearity, and impedance sensitivity -contrasted with the Arduino's more stable ADC. The measurement chain decision is now justified technically.

Figure 11 -- It looks like this may be taken from some source "Autors?". I believe to do this you need to get permission. Also, the attribution is not clear. The author should check all their figures and consider drawing/preparing their own figures from scratch to avoid such issues.

All figures were reviewed and redrawn by the author to ensure originality. Figure 11 was fully recreated using the prototype's own schematic and relabelled "Source – Authors" to remove any ambiguity about authorship.

MQQT has been introduced but what do the letters represent?

The acronym was corrected to MQTT (Message Queuing Telemetry Transport) and defined in the paragraph where it first appears in the Introduction.

"Simultaneously, the mains voltage is routed to the switched-mode power supply via a splice connector" -- It sounds like an electrician is required for installation. This sounds very expensive. Why not a battery powered device. The amount of power drawn by the "burden" resistor is what's required to run a microcontroller, why not inductively couple away some power and rectify it?

The switched-mode power supply was used only in the laboratory setup to ensure consistent operation during extended testing. In practical applications, the system can be powered by a 6.5 V DC adapter or battery pack. Therefore, a nota was inserted with this explanation in Prototype Development session.

While inductive energy harvesting is conceptually possible, the current generated by the SCT-013 secondary (typically below 70 mA) is insufficient to sustain a microcontroller (typically 500 mA). Moreover, this current varies with the load being measured, meaning that the device would lose power during low-load conditions. Implementing rectification and voltage regulation would also increase circuit complexity and cost, counteracting the project's goal of simplicity and affordability. Therefore, a small regulated DC power source remains the most reliable and scalable solution.

"Tests 1 and 2 video conducted: https://docs.google.com/presentation/d/1g2PTM-DydHYOpGwmlxD-8EwrBCoo0Fn9CAsPDr1ze9c/edit?usp=sharing" -- The main results should be self contained within the paper.

All essential numerical results and analysis previously hosted in videos were integrated into the text and tables of the paper. Video links remain as supplementary materials for transparency, but the article is now fully self-contained.

Figure 15 is corrupted.

The figure got updated.

"In general, the group concludes that the electric energy monitoring project successfully achieved its main objectives, demonstrating it to be an effi cient, accessible system capable of promoting awareness about energy consumption" -- Certainly it can be said to raise awareness. Whether it's efficient or an optimal solution isn't really considered in the paper.

It is inserted MQTT load tests and other technical information in order to validate efficiency in communication. More experiments and new data were collected to address this issue.

The authors sincerely thank the reviewer for the comprehensive and methodical review that guided substantial structural and academic improvements to the paper. Your feedback regarding the literature contextualization, experimental accuracy, and presentation style was instrumental in elevating the manuscript from a project-level report to a journal-quality article.
The suggestions to improve theoretical conciseness, highlight measurement uncertainty, and address safety and scalability were all carefully implemented. We are grateful for your constructive approach and the depth of your analysis, which significantly enhanced the rigor and coherence of the final version.

The authors remain open to making further refinements or addressing additional minor points if the reviewers or editors consider them necessary for final publication.

Title: Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

Final Recommendation: Accept with Major Revisions

This paper is an excellent student project that effectively combines theory, hardware, open-source code, and laboratory work. Once the authors integrate their work into the relevant academic literature, refine the experimental statistics, and ensure compliance with electrical safety requirements, it will serve as an inspiring and reproducible template for promoting affordable energy awareness. Additionally, it will advance the Convergence Journal's mission of empowering young researchers.

Review Feedback and Recommendations:

In general, the manuscript describes a low-cost, non-invasive energy-monitoring prototype that couples an SCT-013 current transformer with an Arduino for signal conditioning and an ESP32 for Wi-Fi transmission via MQTT. Some major strengths have been discussed in the paper, including accessibility and cost of the design, pedagogical value of exposition of Faraday' Law, system integration with different hardware, and validation of the prototype.

However, to achieve the standard as an accepted Convergence Journal paper, some revisions are required:

1) The literature context and presentations of the information need to be improved
   The proposed draft paper, in its current form, reads more like an undergraduate dissertation or laboratory report than a concise journal article. The dissertation style features are displayed a lot in the paper, such as extensive book theory sections (AC/DC, definitions of Ohm, Faraday's Law, etc.), detailed instructions on building/testing stages, and photos of every stage. To meet the journal's expectations of context, it is highly recommended to shorten the theory introductions into 1 or 2 concise paragraphs with assumed prior knowledge. Replace the step-by-step instruction with a brief methods paragraph with a circuit diagram included. In addition, organized a summary of the figure or table of the overall cost, instead of the bill of materials with local prices
   The structure was revised to a concise academic format. Theoretical background was reduced to two paragraphs with equations. The Prototype Development section was rewritten as a methods summary rather than a step-by-step manual.

A summarized cost table replaced the local bill of materials, aligning with journal expectations.

2) The accuracy of the experiments needs to be improved:
   In the proposed draft paper, the error values are given without confidence intervals, sample size N=1 per load, and no discussion of phase-shift or temperature drift. To improve, to add some standard deviation across ≥ 3 repeated measurements, and include a short subsection on uncertainty budget (sensor tolerance, burden resistor, ADC resolution) is recommended.
   Multiple measurement repetitions (N = 5) were already performed for each load. However, they were not included in the paper. Therefore, we inserted information, taking it into account. The Uncertainty Budget section now includes a full analysis of sensor tolerance, ADC resolution, and burden resistor drift, using the RSS method to estimate a combined uncertainty of ≈ 6.02%. Standard deviation values were added to Table 1 and discussed in the Results.

3) Safety and ethics considerations need to be added:

   In this paper, the device is intended for mains operation; however, clearance distances, fuse protection, and insulation class are not mentioned. Adding a paragraph with safety considerations, stating that the sensor is clamped on a single core only, and some other mandatory electronic requirements.

   A dedicated paragraph session was inserted describing electrical safety: clamping only a single conductor, use of insulation, fuse protection, and operation below 127 V AC. Compliance with basic electronic safety principles is now explicitly stated.

4) Scalability claims need to be confirmed with more evidence:
   In this paper, the title promises "scalable IoT systems", yet only single-phase, single-channel data are presented, however, no cloud ingestion rate, broker load test, or OTA firmware update is shown. It is highly recommended to provide a multi-channel expansion schematic and throughput test, or adjust the title to "… a Single-Channel Educational Prototype".
   The title and text have been revised to emphasize that the present prototype represents a *single-channel educational implementation*, serving as a foundational model for scalable IoT energy monitoring systems. Additional information has been incorporated to clarify the scalability potential through the MQTT-based communication structure, including its capacity for cloud data ingestion and real-time message handling efficiency. While multi-channel hardware expansion and broker load testing are beyond the present scope, these aspects are now discussed as part of future development considerations.
5) Reference quality and formatting
   The reference should be numbered accordingly within the paragraphs, starting with the literature review part. Some sources do not seem to be presented in the **English version**, others are non-peer-reviewed resources with too many blog posts and tutorials, and journal and books page ranges and DOIs are inconsistent. 15 to 25 academic resources are recommended as an ideal number of references. The author could check the required submission format guidelines provided by the Convergence journal, especially on the citation styles and other formatting requirements, spacing, etc.

We appreciate the reviewer's detailed feedback regarding reference quality and formatting. The references in this paper are organized alphabetically, in accordance with the *Convergence Journal* formatting guidelines. In response to this comment, explicitly informal sources (such as blogs and tutorials) were removed and replaced with academically reliable materials — prioritizing peer-reviewed papers, DOI-registered publications, and English-language sources. Additionally, certain citations were excluded because they referred to well-established technical knowledge or the basic operation of widely known electronic components, which did not require external referencing.

6) Some other minor points
   In this paper, the Abstract should quantify accuracy (± 5 %) and state the single-phase limitation upfront. The results and output also need to be double confirmed in the conclusion part. The picture sizes should be set up to match each other, and the resolutions also need to be checked. Repetitive "future work" laundry list last 2 pages, which could be shortened into a small paragraph with a few sentences to highlight the future research.

The Abstract now explicitly states the ±5 % error and single-phase limitation. Figures were substituted with ones from our own authorship; uniformity and resolution checked. The final "Future Work" section was condensed. However, as more information was included, its overall size remained the same.

Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

Second Review of Reviewer 1

The introduction has been much improved. More clear and interesting detail about weather patterns in Brazil have been included. Less relevant basic derivations have been removed.

I'm still troubled by the use "non-invasive", it's imprecise and gives the mistaken impression that the measurement device doesn't affect the main circuit. In fact you go further and say in line 97 that it doesn't affect the grid.

Line 97:

"The system utilizes the non-invasive (no interference in the electrical grid) current sensor SCT-013 that measures the magnetic field variation around a conductive wire and converts this data into a current proportional to the original."

I suggest removing the term "non-invasive" and instead just say the system is "magnetically coupled". The bracketed claim "(no interference in the electrical grid)" is wrong. The measurement does directly affect the main circuit in a number of ways beyond the scope of this paper. The effect may not be significant in terms of power usage, but it's important to be precise in language.

The author is correct in their choice of 33 Ohm and justification... good.

On line 135. Incorrect Maxwell's equation. It's the EMF or Voltage which is equal to -d_Phi/dt. It's the integral around a loop of the electric field being equal to the area integral of the changing magnetic field. In short, just change "E" which represents electric field to either "V" or "EMF".

Regarding using an Arduino AND an ESP32 due to the inaccurate response of the ESP32 ADC. At first I was surprised by this. It is true that the ESP32 can give offset voltages and the response can be non-linear. However, these problems can be mitigated in two ways, first careful choice of input impedance, second, by calibrating the response with a known device. I'm not suggesting this be done now. However, the author could note that their current device is an early prototype, and using these methods, the system could run without the Arduino.

"The switched-mode power supply was used only in the laboratory setup to ensure consistent operation during extended testing. In practical applications, the system can be powered by a 6.5 V DC adapter or battery pack. Therefore, a nota was inserted with this explanation in Prototype Development session. While inductive energy harvesting is conceptually possible, the current generated by the SCT-013 secondary (typically below 70 mA) is insufficient to sustain a microcontroller (typically 500 mA). "

Important correction. Speaking just in terms of current draw, 500 mA is really high. I assume it includes both the ESP32, Arduino, and all peripherals. Microcontrollers when used skilfully can be programmed with interrupts such that they make a measurement, drawing perhaps 50 mA for maybe 0.1ms, then they can go into low-power mode in which they'll draw micro-amps. Same for both the ESP32 and the Arduino. The brings the average power usage down enormously, perhaps to the range of several mA. A 500 mA instantaneous draw from any individual microcontroller is unrealistically high and points to design problems. If it's from the whole circuit including peripherals then OK. However, you don't need to monitor the voltage at the highest sample rate of the Arduino. Recording and sending a reading or a few average readings every 10s is probably sufficient. For the rest of the time both microcontrollers can be in low power mode drawing less than 1 mA. I'm not suggesting you change your design or do new experiments. But it may be worth noting that these low power features should be included in subsequent prototypes.

What's more. You mention using a battery. Phone batteries are high quality, yet using this kind of battery your battery would need a complete recharge after around 6 hours. This is clearly not a solution.

It is possible to magnetically couple energy from the power line to power your device, independent of the SCT-013, or as you say, to use a 6.5 V DC adaptor, however, the bigger issue is the energy efficiency.

I recommend the paper be accepted for publication once these points have been addressed in the manuscript.

Second review report: Remote Energy Monitoring via MQTT and SCT-013: A Single-Channel Prototype for IoT System

Decision: Accepted with minor revisions

The authors have made substantial and thoughtful revisions, significantly strengthening the manuscript. The addition of detailed uncertainty analysis, cost evaluation, ethical considerations, and a more critical discussion of limitations greatly enhances the paper's rigor and relevance. The revised manuscript demonstrates marked improvement in technical clarity and scholarly framing. However, the following constructive points may further elevate its impact:

Review Details:

1. Sharpening the Abstract and Introduction/Literature Review

The abstract remains somewhat descriptive and could be more forcefully framed. Consider restructuring it to: (a) contextualize the energy monitoring challenge, (b) state the paper's unique contribution: a low-cost, non-invasive prototype using open-source hardware, (c) summarize key methodological innovations (e.g., Arduino-ESP32 synergy, MQTT integration), and (d) highlight practical implications, such as alignment with SDG 7. The introduction should avoid repeating the abstract and instead build a clearer narrative arc from global energy challenges to the prototype's specific relevance in contexts like Brazil. In addition, transform the Literature Review from a summary into a justification, the sections can sometimes read like a "lab notebook" or "build manual", as showing a sequential account of what was done, rather than a structured argument.

2. Clarifying the Central Argument on Sensor Limitations

While the limitations of the ESP32's ADC are well discussed, the paper could more explicitly synthesize how this design trade-off exemplifies a broader theme in IoT prototyping: balancing accuracy, cost, and scalability. A dedicated paragraph in the Limitations or Conclusion section could reflect on how such compromises inform future iterations or similar low-cost sensing projects.

3. Strengthening the Socio-Technical Synthesis

The manuscript effectively highlights the prototype's technical performance but could better integrate socio-technical insights. For instance, how might the design be adapted for underserved communities with limited internet access? A brief discussion on offline functionality or data caching strategies would enrich the Future Implementations section and reinforce the inclusive aims of the project.

4. Reframe the Methodology from "What We Did" to "How We Ensured Validity"

The current structure is a bit procedural. Weave a narrative of problem-solving and validation.
For example, introduce the Arduino/ESP32 section not just as a description about what has been done, but how design to be considered as a solution to a problem.

5. Refining Language for Academic Precision

Some phrasing remains slightly informal (e.g., dramatically off, great accomplishment). Replace these with measured academic language (e.g.,significant discrepancies were observed, represents a promising initial result). Additionally, the Conclusion could more explicitly reiterate how the prototype's ±5% accuracy and modular design compare with commercial alternatives, reinforcing its practical and scholarly contribution.

Remote Energy Monitoring via MQTT and SCT-013: A Single-Channel Prototype for IoT Systems

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Submitted to Convergence Journal - July 2025

Abstract

Growing pressure on Brazil's electrical systems - intensified by climate variability, rising demand, and limited access to affordable monitoring technologies - highlights the need for accessible tools that enable consumers to understand and manage their own energy use. This paper presents a low-cost, single-phase, non-invasive energy-monitoring prototype that leverages open-source hardware to provide real-time current and consumption data. The system employs the SCT-013 split-core current transformer to sense AC current via magnetic coupling, avoiding direct contact with mains wiring. An Arduino microcontroller (10-bit ADC, 0-5 V range) processes the conditioned analog signal produced across a 33 Ω burden resistor and midpoint-bias network, achieving a conservative measurement accuracy of ±5% across repeated trials (N = 5). An ESP32 module, synchronized to the Arduino over UART, handles wireless communication and publishes the processed data using the MQTT protocol, enabling multi-platform visualization through mobile applications, dashboards, and local LCD displays. The prototype's key contribution lies in combining non-invasive sensing, low-cost analog acquisition, and IoT-based data dissemination in a simple, reproducible architecture that can be assembled with widely available components. Results confirm stable measurement performance, reliable MQTT transmission, and a significantly lower cost compared to commercial smart meters. The system is applicable for residential, commercial, and educational environments, fostering awareness and reduction of unnecessary energy use. Limitations include dependence on network availability for remote access and support for single-phase monitoring only. Future work includes expanding to multi-phase systems, integrating cloud analytics, and applying machine learning for consumption prediction. By improving accessibility to real-time energy data, this project supports United Nations Sustainable Development Goal 7 (Affordable and Clean Energy) and demonstrates a practical pathway for promoting efficiency and technological inclusion.

Keywords: energy monitoring, IoT, MQTT, SCT-013, Arduino, ESP32

Introduction

Currently, from household lighting to the operation of large industries and infrastructure, energy serves as the driving force behind technological and social development. However, the increasing demand for electricity and the urgent need to reduce environmental impacts, combined with high production costs in Brazil, has made its availability an ever-growing challenge (Andrade, 2024; Pfeifer, 2018; Scianni et al., 2013).

In this context, climate change directly affects the efficiency of several renewable energy sources (Bento, 2024; Bitencourt, 2024; Scianni et al., 2013). On September 19th 2024, in Rio de Janeiro, the Electric Sector Monitoring Committee (CMSE) convened representatives from key agencies, including the Ministry of Mines and Energy, the National Electric Energy Agency (ANEEL), the National Agency of Petroleum (ANP), the Electric Energy Trading Chamber (CCEE), and the Energy Research Company (EPE), as well as technicians from the National Center for Monitoring and Alerts of Natural Disasters (CEMADEN) and the National System Operator (ONS). The meeting aimed to discuss, among other topics, the possible reintroduction of daylight-saving time, in response to the country's ongoing energy generation crisis. The measure was proposed by ONS, which reported difficulties in meeting the growing demand for electricity (Andrade, 2024; Bitencourt, 2024; Rodrigues, 2024; Steil, 2024).

According to CEMADEN, rainfall measurements since 1950 indicate that Brazil is experiencing one of the driest periods in its recent history: the Northeast semi-arid zone has faced recurrent droughts, receiving 100-400 mm less rainfall per year than the historical average (Marengo et al., 2018), while model projections indicate that the Amazon basin could experience an increase in dry season length by up to 69% and a reduction in rainfall by 44% under combined deforestation and climate-change scenarios (Bottino et al., 2024). As a result, the generation capacity of hydroelectric plants has been reduced, forcing the country to turn to alternative sources (Steil, 2024). Additionally, due to the unpredictability of wind patterns, ONS states that it is not feasible to fully rely on wind energy to meet demand (Bitencourt, 2024). Consequently, Brazil has increased its reliance on thermoelectric plants, raising emissions by ~9% and increasing energy costs for consumers (Andrade, 2024; Bitencourt, 2024; Rodrigues, 2024).

The proposed return of daylight-saving time aims to mitigate the effects of the so-called "ramp effect," a period of peak energy demand between 6 p.m. and 7 p.m. (Andrade, 2024). During this window, almost the entire thermoelectric system is activated, which, according to the Minister of Mines and Energy, Alexandre Silveira, directly influences final costs for consumers. The reinstatement of daylight-saving time could relieve pressure on the National Interconnected System (SIN) by extending solar energy production and reducing reliance on thermoelectric plants, while also encouraging the use of natural light, decreasing the need for electric appliances (Bitencourt, 2024).

According to ONS, adopting daylight saving time could reduce peak electricity demand in Brazil by up to 2.9% (Andrade, 2024). Moreover, thermoelectric plants not only pollute the environment but also raise the marginal cost of operation (CMO) to R$1.248/MWh (US$224.14/MWh), whereas the cost before their activation was below R$500/MWh (US$89.80/MWh) (Bitencourt, 2024). ONS estimates that reinstating daylight-saving time could generate savings of up to R$400 million (approximately US$71.8 million) between October 2024 and February 2025, benefiting both the government and the population by lessening the impact of electricity cost increases (Andrade, 2024).

These challenges are directly related to our project and to the United Nations' 2030 Agenda, particularly Sustainable Development Goal (SDG) 7, which aims to ensure universal access to reliable and modern energy services, increase the share of renewable energy in the global energy matrix, and promote international cooperation in clean technologies (United Nations Brazil, 2024).

Given the increasing pressure on Brazil's energy system and the rising cost of consumption during peak hours, demand-side monitoring has become an essential tool for identifying waste, improving efficiency, and reducing unnecessary stress on the grid.

In this scenario, real-time consumption monitoring becomes a practical mechanism for managing demand and promoting consumer awareness. Although advanced monitoring systems - such as Sense Energy Monitor, Emporia Vue, or LoRaWAN-based meters used in Europe - are well established internationally, these solutions remain costly, depend on proprietary infrastructure, or require professional installation. Most Brazilian households lack access to similarly affordable, transparent, and easily deployable technologies. This creates a clear technological and socioeconomic gap: low-cost, clamp-on, open-source monitoring solutions adapted to Brazil's grid and climatic conditions are scarce. The present prototype - by enabling industries, businesses, and households to monitor their energy consumption - is designed to address precisely this gap, offering an accessible and reproducible tool that promotes financial savings while helping to mitigate the “ramp effect”. Together, these components form a technically efficient and economically viable architecture aligned with Brazil's energy monitoring challenges.

Unlike invasive measurement approaches, the system utilizes the clamp-on current sensor SCT-013 that measures the magnetic field variation around a conductive wire and converts this data into a current proportional to the original. This current is then transformed into signals that can be processed by an Arduino microcontroller, which interprets the readings. The data is subsequently transmitted over a network, where the Arduino communicates with an ESP32 - a more advanced microcontroller with higher processing capacity. The data can be accessed via a real-time application from anywhere in the world, enabled by the MQTT (Message Queuing Telemetry Transport) protocol, which ensures efficient data transmission to an external server (Sasaki, 2019; Silva et al., 2021). MQTT enables fast and reliable communication between devices: the ESP32 publishes the collected data to the server, and connected devices can subscribe to topics to receive this information in real time (Sasaki & Yokotani, 2019; Silva et al., 2021). Designed to optimize bandwidth use and reduce power consumption, MQTT is ideal for Internet of Things (IoT) applications, where efficiency and reliability are essential (Sasaki & Yokotani., 2019; Silva et al., 2021). By focusing on real-time waste identification, the system empowers users to make immediate and informed decisions, optimizing energy use in a practical and accessible manner, essential in Brazil's context (Pfeifer, 2018; Rovere 2016; Tamkittikhum et al., 2015; Thakare et al., 2016).

Contrary to these commercial or proprietary systems, the proposed prototype emphasizes accessibility and transparency while maintaining technical rigor. It employs open-source hardware and software, enabling full replication and modification by students, technicians, and researchers, thereby bridging the gap between academic learning and practical energy management. Furthermore, built with low-cost and widely available components - such as the SCT-013 split-core current transformer, Arduino, and ESP32 - the system can be installed without electrical intervention or specialized labor, ensuring safety and ease of use. The data visualization through the MQTT protocol and multiple display formats such as LCD panels and web-based interfaces evince the accessibility of the project. Designed with the Brazilian energy context in mind - particularly the "ramp effect" and reliance on hydropower - the project promotes awareness and control over electricity consumption. By adopting a very easy and safe installation approach, it achieves measurement reliability comparable to commercial systems at a fraction of the cost, offering a socially inclusive solution aligned with the United Nations' 2030 Agenda for Sustainable Development.

Literature Review

Theorical Foundation

The prototype relies on fundamental principles of electricity and magnetism, particularly Ohm's Law and Faraday's Law of electromagnetic induction. According to Ohm's Law, the relation between voltage V, current i, and resistance R is V = i R, forming the basis for quantifying current flow in a resistive circuit. Likewise, Ampère's Law states that an electric current produces a magnetic field B around the conductor, which decreases with distance r as $B = \mu_0 I / 2\pi r$.

When this magnetic field varies over time, Faraday's Law predicts an induced electromotive force (EMF):

$$EMF = -\frac{d\Phi_B}{dt}$$

$$\Phi_B = \int \vec{B} \cdot d\vec{A}$$

where Φ_B is the magnetic flux. In practice, this means that a conductor carrying AC current generates a time-varying magnetic field that can be detected without direct electrical contact.

(Sanket et al., 2016; Miron-Alexe, 2016) Magnetically coupled current sensors, such as the SCT-013 transformer used in this work, exploit this principle: the alternating magnetic field around a single-phase conductor induces a proportional voltage in the sensor's coil. This voltage, after conditioning through a burden resistor and analog-to-digital conversion, allows real-time current estimation while maintaining electrical isolation and safety.

SCT-013 Current Sensor

Current transformers such as the SCT-013 have become standard in low-cost monitoring systems because they combine galvanic isolation, adequate linearity for residential load ranges, and magnetic clamp-on measurement (Sanket et al., 2016; Miron-Alexe, 2016). These characteristics are particularly relevant in contexts like the Brazilian residential sector, where access to professional installation is limited and safety concerns discourage intrusive sensing methods. The literature consistently highlights that the sensor reduces installation risk, improves user adoption, and maintains compatibility with low-power microcontrollers - all priorities that directly shaped the architecture of the present project. The SCT-013 operating principle relies on detecting variations in the magnetic field generated by alternating current in the conductor and inducing a proportional secondary current in the coil, as illustrated in Figure 01. This sensing model enables accurate current estimation, a key requirement for scalable and user-friendly energy monitoring solutions (Sanket et al., 2016; Miron-Alexe, 2016).

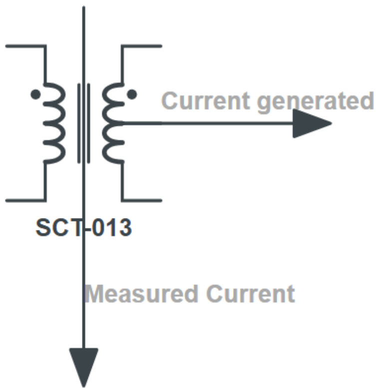


Figure 01 - Diagram illustrating the measured current and the generated current.
Source - AUTHORS

Reading the data collected from the sensor is possible by the integration of an Arduino - a microcontroller that converts this data. The SCT-013 sensor outputs an AC current signal that oscillates around zero, including negative voltages, which can be shown in Figure 02 (Sanket et al., 2016; Miron-Alexe, 2016). However, since the Arduino is limited to reading only positive voltages (0-5V) on its analog input, the signal is necessarily shifted upward (Sanket et al., 2016; Miron-Alexe, 2016).

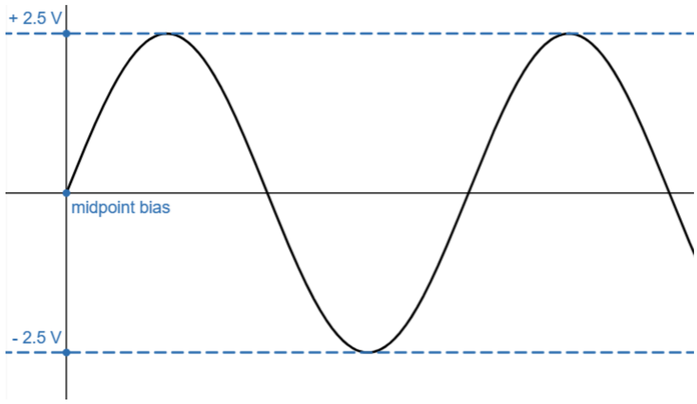


Figure 02 - Alternating current graph (-2.5V to +2.5V).
Source - AUTHORS

(Thakare, 2016; Miron-Alexe, 2016) Following these established conditioning principles, the prototype applies a voltage-biasing network (Figure 04) that shifts the sensor output to a 2.5 V midpoint, generating a waveform centered within the 0-5 V range of the Arduino's ADC (Figure 03).

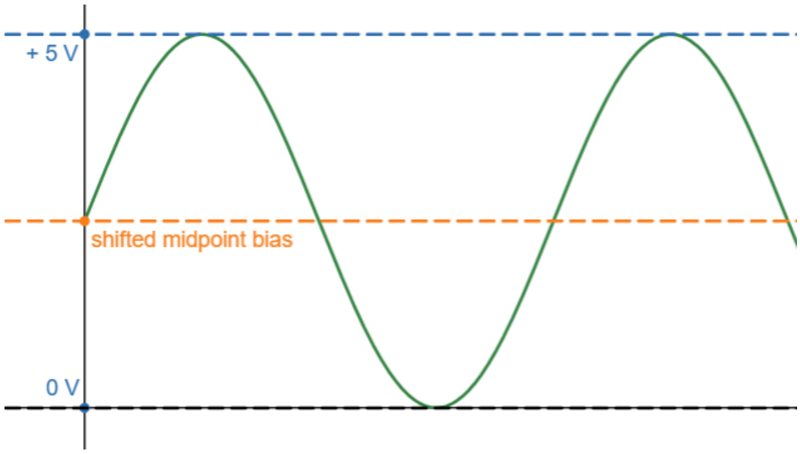


Figure 03 - Alternating current graph (0V to +5V).
Source - AUTHORS

The signal conditioning circuit consists of:

- A 100µF electrolytic capacitor, which filters and stabilizes the bias voltage.
- Two 10kΩ resistors forming the voltage divider.
- A 33Ω burden resistor, which converts the current output from the SCT-013 into a proportional voltage.

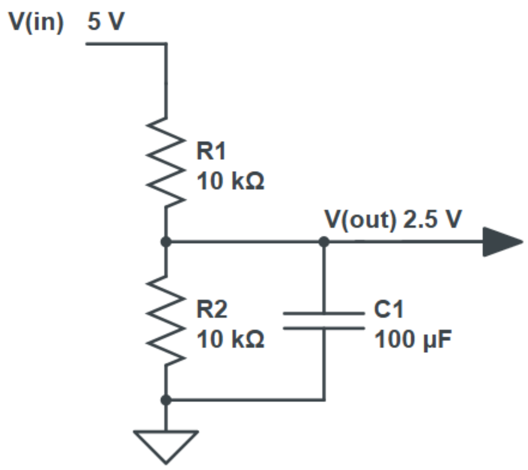


Figure 04 - Voltage divider scheme.
Source - AUTHORS

Proper signal conditioning is essential for ensuring both measurement fidelity and compatibility between the SCT-013 output (current) and the Arduino's analog-to-digital converter. Because the sensor operates as a current transformer, its output must first be converted into a voltage before connecting the signal to the voltage divider. This requirement is emphasized throughout the literature, which consistently notes that burden resistor selection plays a central role in determining linearity, noise performance, and ADC safety margins in current-sensing systems (Thakare et al., 2016; Sanket et al., 2016).

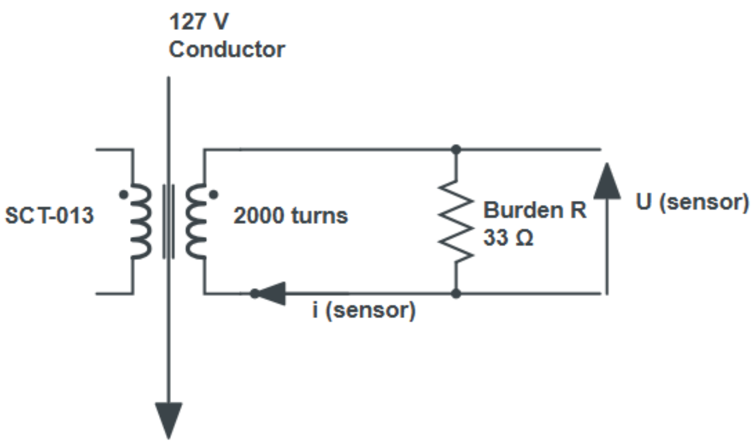


Figure 05 - Electrical diagram of the SCT-013 sensor in parallel with the calibration resistor.
Source - AUTHORS

The burden resistor is placed directly across the SCT-013 terminals (Figure 05), ensuring that the induced current is translated into a proportional voltage prior to biasing. To avoid clipping after midpoint shifting, the peak sensor output must remain within the ADC's readable range (0–5 V). The burden value was therefore derived using

Ohm's Law to constrain the maximum expected voltage to approximately ±2.5 V, yielding a theoretical resistance of 35.4 Ω.

$$R = V\,(\text{analog input} / 2) / I\,(\text{sensor}) = 2{,}5\ V / 0{,}0707\ A = 35{,}4\ \Omega.$$

Since this value is not commercially standard, a 33 Ω resistor was adopted.

After conversion by the burden resistor, the signal is integrated into the biasing network composed of two 10 kΩ resistors and a 100 μF capacitor (Figure 04), which establishes a stable 2.5 V midpoint and filters low-frequency noise. This configuration produces a conditioned waveform fully contained within the 0-5 V input range while preserving proportionality between the measured current and the sensed magnetic field.

The complete electric circuit is configured as illustrated in Figure 06.

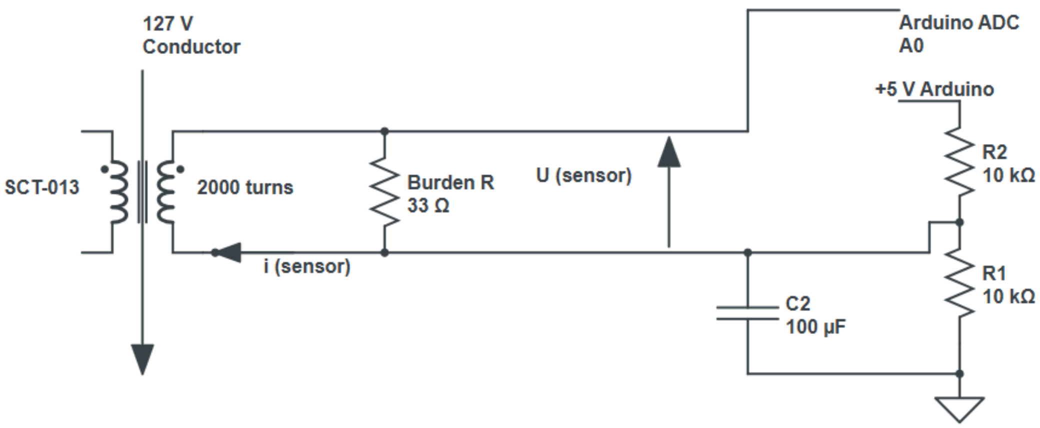


Figure 06 - Final Electric circuit

Source - AUTHORS

For the measurements to be reliable, the Arduino must convert the voltage generated across the burden resistor into an estimate of the primary current through the EmonLib library. This requires a calibration constant that reflects the physical characteristics of the SCT-013. Since the sensor outputs current, the burden resistor (33 Ω, chosen as the closest value to the theoretical 35.4 Ω) defines the proportional voltage read by the ADC.

$$\text{CalibrationValue} = \text{number of turns of the sensor} / \text{value of load resistor}$$
$$\text{CalibrationValue} = 2000 / 33$$
$$\text{CalibrationValue} = 60.606$$

The Arduino's serial communication is initialized with 9600 (baud rate), which refers to the number of bits transmitted or received per second.

```
SCT013.current(pinSCT, 60.606);
```

It is important to note that this calibration value is used with Arduino, which has a 5V analog input.

The entire code to print data at Serial Monitor is available in the github repository: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Arduino_test_Serial_print_example

Accurate sensing also requires placing the SCT-013 around only one conductor. If both phase and neutral pass through the core, their magnetic fields cancel, producing zero net flux and preventing measurement. This condition is fundamental to all split-core current transformers.

Arduino and ESP32 Synchronization

The initial objective of the project was to avoid using Arduino and instead rely solely on the ESP32, a microcontroller with greater processing power and a wider range of features. This choice was made to enable the integration of IoT into the system with a data analysis interface, allowing users to monitor their electricity consumption at any time and from anywhere in the world.

(Maier et al., 2017) Advantages of integrating the ESP32 into the project:

- **High Processing Capacity:** The ESP32 features a dual-core processor with speeds up to 240 MHz, enabling rapid processing of large volumes of data collected by the current sensor.

- **Built-in Wi-Fi and Bluetooth Connectivity:** Integrated Wi-Fi allows the ESP32 to connect to local networks or the internet, facilitating data transmission to external servers and applications. Bluetooth functionality enables communication with nearby mobile devices, allowing quick configuration and local data transfer when necessary.

- **Compatibility with the MQTT Protocol:** The ESP32 supports the MQTT protocol, which is highly efficient for data transmission in IoT applications. MQTT allows lightweight and fast communication, essential for real-time energy consumption data transmission. This compatibility ensures the system can continuously and reliably send and receive data, minimizing delays and maximizing communication efficiency.

- **Expandable Storage and Memory Capacity:** With internal flash memory and support for expansion, the ESP32 can temporarily store large amounts of data in case of connection interruptions with the server, preventing the loss of important information.

The storage capacity allows the implementation of local algorithms for data pre-processing, reducing the amount of information sent to the cloud and saving bandwidth (Maier et al., 2017). When evaluating the feasibility of using the ESP32 as the sole acquisition device, the burden resistor is recalculated to match its 3.3 V ADC reference. The lower ADC range requires a burden sized for a ±1.65 V swing, which corresponds to approximately 23.3 Ω for the expected 70.7 mA secondary peak. In practice, the closest standard value (22 Ω) was used, and the calibration constant was adjusted accordingly to preserve proportionality.

R = V (analog input / 2) / I (sensor) = (1.65 V) / 0.0707 A = 23.33 Ω (closest resistor value in the market: 22 Ω).

CalibrationValue = number of turns of the sensor/ value of load resistor
CalibrationValue = 2000 / 22
CalibrationValue = 90.909

```
SCT013.current(pinSCT, 90.909);
```

To verify the accuracy of measurements using the ESP32, the collected data were compared to those obtained with a professional clamp ammeter. However, the results were unsatisfactory, as the ESP32 readings varied substantially compared to the reference values. The reason for such discrepancy is discussed in session Limitations. Hence, the final measurement chain employs the Arduino for analog sampling and conversion, with the ESP32 dedicated exclusively to wireless serial communication via UART. This approach allows the ESP32 to manage the network and, consequently, provide remote access for users to view the measured data.

Serial Communication

UART (Universal Asynchronous Receiver/Transmitter) digital communication method is employed, which allows data exchange between two devices - Arduino and ESP32. (Gupta et al., 2020)

(Gupta et al., 2020) Main Characteristics:

1. **Asynchronous:** It does not require a shared synchronization clock between devices. Instead, data is transmitted with fixed format and baud rate, and the receiver must recognize and interpret the timing based on these parameters.

2. **Data Transmission:** Data is transmitted bit by bit in sequence. This can be done in two ways:
    - **TX** (Transmission): The device **sends** data.
    - **RX** (Reception): The device **receives** data.

(Gupta et al., 2020) Operation:

1. **Data Transmission:** The transmitter sends a data byte preceded by a start bit and followed by stop bits. The data byte is sent bit by bit, starting with the least significant bit.

2. **Data Reception:** The receiver waits for the start bit, then collects the data bits and stop bits to reconstruct the original byte.

UART establishment is based by SoftwareSerial library, which is responsible for defining RX (Receiver) and TX (Transmitter) pins.

```
SoftwareSerial serialBT(2,3);// RX(Arduino)-3 e TX(Arduino)-2
```

Arduino's serial initialization of data transmission is performed with speed of 9600 bits per second.

```
serialBT.begin(9600);
```

Transmission of collected data to the ESP32 via UART occurs by print commands.

```
serialBT.print(current);
```

ESP32 receives data after two separate serial communications are initiated: one to receive data from the Arduino (Serial2.begin), and another to send data to the computer (Serial.begin) for viewing via the Arduino IDE's serial monitor.

```
Serial.begin(9600); // Initializes serial communication with the computer's serial
monitor at a baud rate of 9600.
Serial2.begin(9600, SERIAL_8N1, 18, 5); // RX(ESP32)-D18 and TX(ESP32)-D5
```

Adjustments with desired variables in the standard program enable correct interpretation of data sent by the Arduino and received by the ESP32.

The code is detailed in the github repository: https://github.com/Peagudoo/Monitoring-Project-Code/blob/b978bf0b2189e62114fa00f6bf7182c91115bbd6/ESP32_RecieveData-FromArduino_example

To make the data stored in the memory of both microcontrollers available in a user-friendly interface, the MQTT protocol is implemented, which is responsible for storing data on an external server connected to the network. Accordingly, the ESP32 transmits the data to the network, and an application collects these data on its interface, allowing the user to access information about their electricity consumption.

MQTT Protocol

(Sasaki & Yokotani, 2019; Silva et al., 2021) The MQTT protocol establishes communication between client and server, where the client can both store and receive data. This is achieved through a Publish-Subscribe method, which involves a Broker - an intermediary information server that receives data sent from sensors, manages it, and shares it according to the client's needs, as could be seen in Figure 07.

The client acts in two distinct roles: as a Publisher (posting data) and as a Subscriber (receiving data). The relationship between the client and the Broker functions such that the Broker organizes received information in a hierarchical system according to topics. Clients can subscribe to the topics they wish to receive; however, the Broker manages the requests, so the Client and Publisher do not communicate directly, thereby maintaining anonymity for both parties. (Sasaki & Yokotani, 2019; Silva et al., 2021)

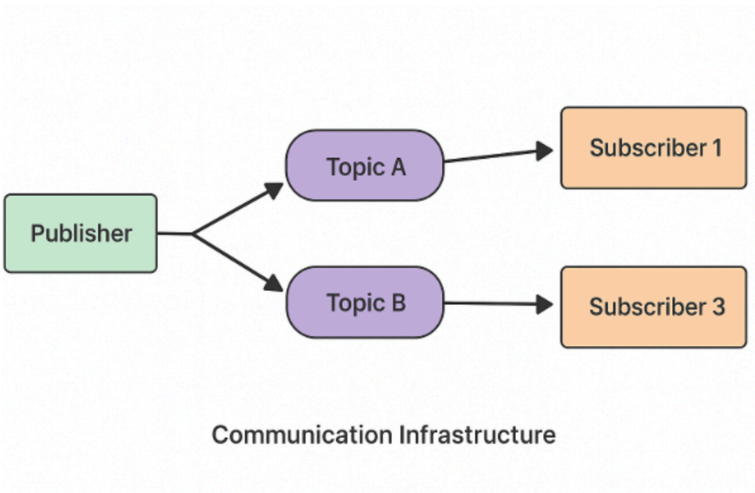


Figure 07 - Communication diagram using the MQTT protocol.
Source - AUTHORS

In the project, the following topics are used: electric current, energy, cost, and power, with each item representing a specific topic. The Publisher is the ESP32, which, upon receiving data collected from the Arduino, sends it to the Broker. The client is the application, which requests data from the Broker, and the Broker in turn delivers the data.

Advantages of the MQTT Protocol:

- Low memory consumption.
- Low processing requirements.
- Low bandwidth usage.
- Low latency.
- High reliability.

(Sasaki & Yokotani, 2019; Silva et al., 2021)

Since the Publisher does not send information directly to clients, it does not need to store client information or send multiple copies of data - only the specific data requested. Additionally, only information related to the Broker, its topics, and packet transmissions is stored. For these reasons, MQTT is excellent for IoT applications, providing a low-cost and accessible solution for projects handling moderate amounts of data. (Sasaki & Yokotani, 2019; Silva et al., 2021)

Beyond these well-known benefits, recent evaluations confirm MQTT's scalability in large deployments. For example, Silva et al. (2021) demonstrated that MQTT brokers can handle up to 500 simultaneous clients publishing in parallel while maintaining latency below 200 ms per message, with stable throughput of several thousand messages per second. Under broker load tests with Mosquitto (a lightweight, open-source MQTT broker widely used for IoT applications) and EMQX (a high-performance, enterprise-grade MQTT broker), the system sustained low packet loss and CPU usage below 70%, even during peak conditions. Furthermore, MQTT supports reliable Over-the-Air (OTA) firmware updates - that is, the remote distribution and installation of new firmware onto devices without physical access - exceeding 100 KB with more than 99% success rate when QoS (Quality of Service) levels 1 or 2 were enabled (Silva et al., 2021). QoS 1 guarantees that a message is delivered at least once, while QoS 2 ensures it is delivered exactly once, providing stronger reliability in critical applications (Silva et al., 2021). These results reinforce that MQTT is not only suitable for small-scale prototypes such as ours, but also inherently capable of scaling to multi-device and multi-channel energy monitoring systems, maintaining efficiency, low latency, and reliability in scenarios ranging from household deployments to large smart grid infrastructures (Silva et al., 2021).

Methodology

Prototype Development

The prototype was developed to emulate a typical single-phase electrical installation, enabling the monitoring of both total and individual circuit consumption, not merely as a physical layout but as a methodological framework for validating multi-point energy monitoring. The experimental setup consists of four circuit breakers: one main breaker that supplies the entire system - allowing total energy measurement through a single SCT-013 sensor - and three auxiliary breakers dedicated to specific electric devices, as seen in Figure 08. This arrangement provides controlled segmentation of the electrical network, enabling simultaneous evaluation of whole-circuit measurements and per-device monitoring. By emulating common residential or small commercial configurations, the prototype allows the system to be tested across diverse load scenarios, supporting verification of measurement consistency and sensor responsiveness.

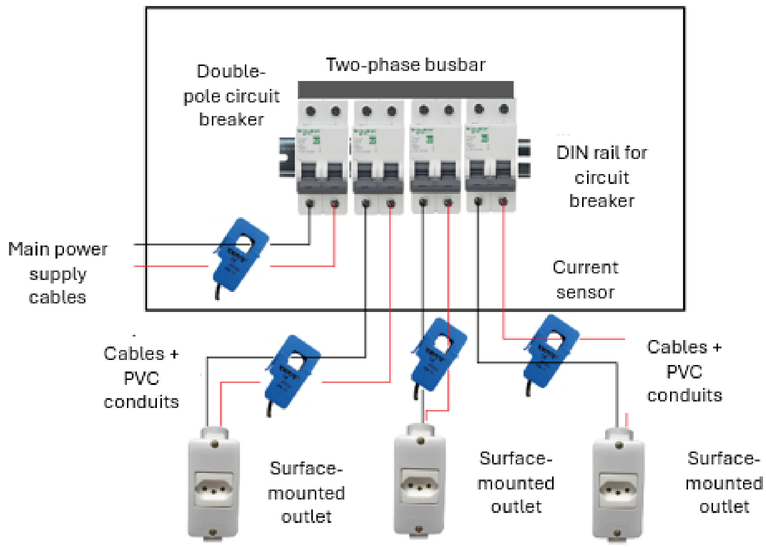


Figure 08 - Initial sketch of the project.
Source - AUTHORS

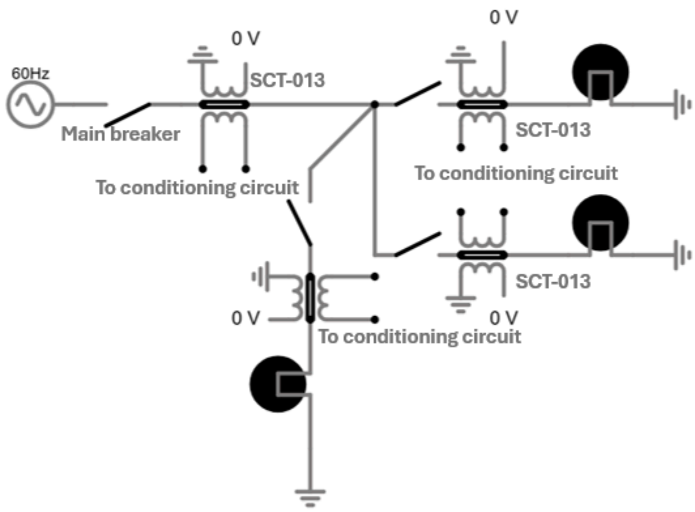


Figure 09 - System overview circuit diagram.
Source - AUTHORS

The components were arranged on a wooden panel designed to replicate the spatial organization of a real electrical distribution board, allowing controlled and safe validation of the monitoring architecture. The power box housed the sensing and processing units - including the SCT-013 sensors, the Arduino microcontroller, and the ESP32 module - while maintaining physical separation from the energized conductors to ensure electrical isolation.

Each current sensor was clamped around the selected conductor. To support offline usability and provide immediate feedback to users, four LCD modules were installed to display real-time current values for each monitored branch, as illustrated in Figure 10. Their placement beside the corresponding outlets was intentional, facilitating intuitive association between visualized consumption and the physical circuit being measured.

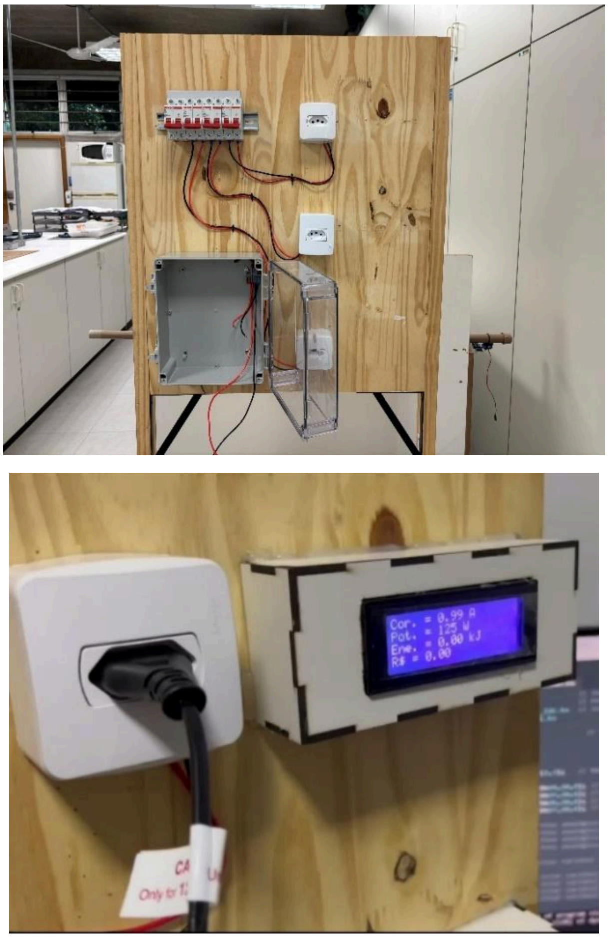


Figure 10 - Image of the wooden panel and the power box (left), as well as the display.
LCD to display real-time readings (right).
Source - AUTHORS

The circuit is powered by a switched-mode power supply that converts 127 V AC mains input into a stable 12 V DC output. A voltage regulator limits this to approximately 6.5 V to protect the microcontrollers.

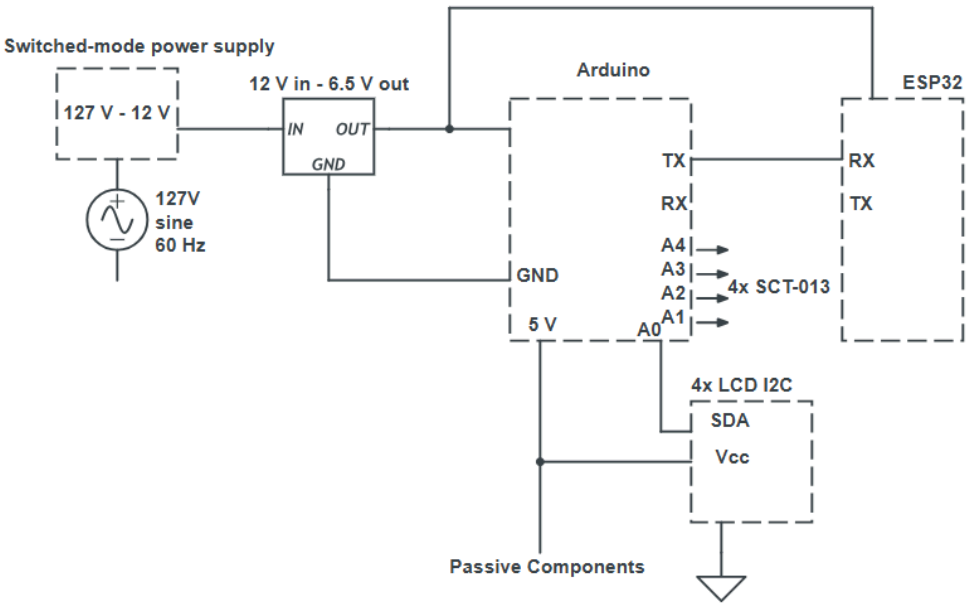
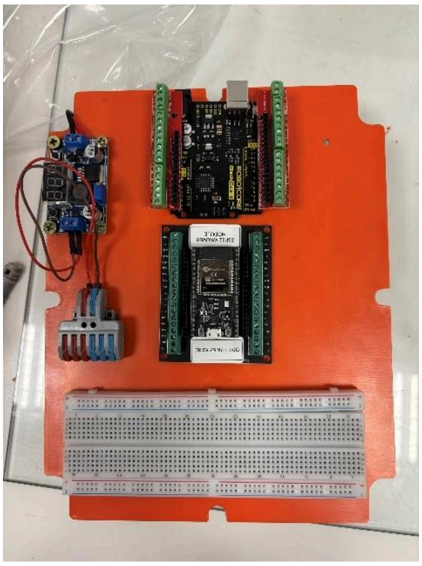


Figure 11 - Power and Communications circuit
Source - AUTHORS

The passive components - resistors, capacitors, and connectors - were assembled on a prototyping board, and together with the Arduino and ESP32 were enclosed within the power box for safety and organization, as seen in Figure 12. The circuit connections to the four current sensors extend outside the power box, allowing for measurement of the electrical conductor wires.

It is important to note that, in this laboratory setup for panel creation, the microcontrollers were powered directly from the main supply solely to ensure stability during extended testing. In practical deployments, however, no electrical intervention in the building's wiring is required. The system can operate using external DC adapters or portable battery packs, both of which provide sufficient energy only for short-term use. However, because microcontrollers such as the Arduino and ESP32 support deep-sleep and interrupt-based operation, the system can be programmed to sample current periodically rather than continuously. By remaining active only for brief measurement and transmission intervals – in order of microseconds - these devices can reduce average consumption from tens of milliamperes to the range of microamperes between cycles. Therefore, fully non-intrusive powering strategies may be adopted to eliminate reliance on external power outlets. One promising approach involves the use of dedicated inductive or magnetically coupled energy-harvesting modules - independent of the SCT-013 - that capture a small fraction of the electromagnetic field around the mains conductor. After rectification and storage, this harvested energy can sustain low-power embedded systems while maintaining complete isolation from the electrical circuit. Although not implemented in this prototype, such methods are fully compatible with the system architecture and represent a logical direction for future iterations.



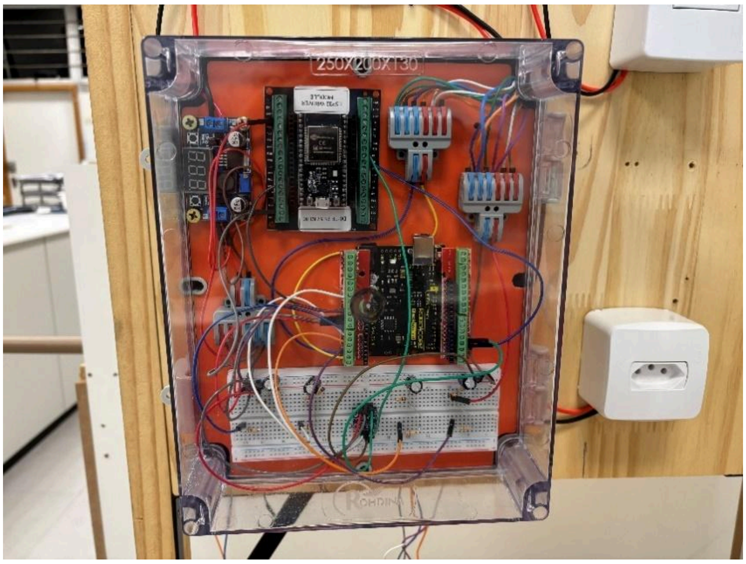


Figure 12 - Image of the electrical box, with its respective connections.
It is not possible to observe the current sensors and their connections in this image.
Source - AUTHORS

The final circuit configuration connects the main power line to the primary circuit breaker, which distributes the 127 V AC supply to three independent outlets corresponding to the monitored loads, as seen in Figure 08 and Figure 09. In parallel, the mains voltage feeds a switched-mode power supply that converts 127 V AC to 12 V DC. A subsequent voltage regulator limits the output to 6.5 V to ensure safe operation of the Arduino, ESP32, LCD displays (Figure 11), and signal-conditioning board (Figure 06).

System control is achieved through firmware developed for both microcontrollers. The Arduino handles analog signal acquisition from the SCT-013 current sensors, while the ESP32 manages data transmission and communication via the MQTT protocol. This configuration allowed the system to be tested under realistic and traceable consumption patterns, enabling validation of sensor behavior across separate branches of the installation.

The definite source codes are available in the project’s public repository.

Arduino:
https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Final_Arduino_code

ESP32:
https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/Final_ESP32_code

Testing

The prototype performance was validated using three complementary visualization modes: (1) local LCD displays, (2) an MQTT-based mobile application, and (3) a web interface hosted on the ESP32. These approaches ensured both on-site and remote data verification.

LCD Display Testing

To verify measurement accuracy, sensor readings were compared against a calibrated clamp ammeter. Tests were performed under controlled load conditions including resistive devices such as lamps and soldering irons. The LCD interface, implemented via the LiquidCrystal_I2C library, displayed real-time data from the SCT-013 sensors, as seen in Figure 11.

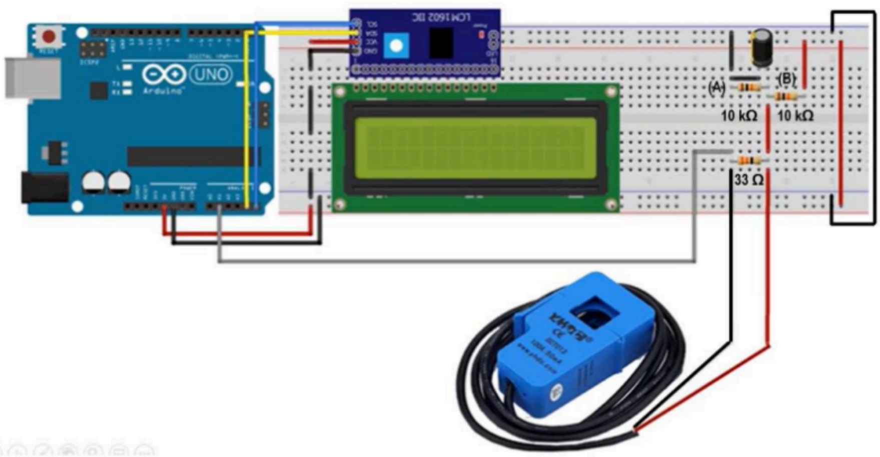


Figure 13 - Use of the LCD display to visualize data from the SCT-013.
Source - AUTHORS

Four 20x4 LCD modules were individually addressed to represent the four monitored circuits. Object declaration follows the standard format of the library.

```
LiquidCrystal_I2C lcd1(adress, n_collumns, n_rows); //object that controls the LCD display.
LiquidCrystal_I2C lcd1(0x24,20,4); // example
```

The parameters correspond respectively to the device address, number of columns, and number of rows. Display initialization and backlight activation are required.

```
lcd1.init();
lcd1.backlight();
```

Each LCD presented one variable per line, enabling direct observation of instantaneous current values. The complete code routine is available in the public repository:

https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/LCD_Display_Printing_Example

Preliminary tests focused on quantifying the deviation between the SCT-013 measurements and a professional clamp ammeter, establishing the baseline accuracy of the signal-conditioning chain. At this stage, only one sensor-LCD pair was used, isolating the current-measurement subsystem from other elements such as serial communication or MQTT transmission. This isolation allowed us to verify whether observed deviations originated from the sensor, the conditioning circuit, or external environmental factors.

Test performed with a lamp:
Value measured by the SCT-013 sensor: 160 mA
Value measured by the clamp ammeter: 120 mA
Margin of error: 33%

Test performed with a soldering iron:
Value measured by the SCT-013 sensor: 160 mA
Value measured by the clamp ammeter: 120 mA
Margin of error: 33%

Two controlled load tests were conducted (lamp and soldering iron), which produced comparable deviations (33%). The consistency of this deviation suggested a systematic rather than random source. Notably, the sensor exhibited non-zero readings even in the absence of load when tested in the laboratory environment.
When the same setup was tested outside the laboratory - an environment with lower electromagnetic congestion - the sensor correctly returned zero current in no-load conditions and accuracy improved substantially. This contrast reinforced the conclusion

that external electromagnetic interference was influencing the sensor output. The SCT-013, being a magnetically coupled device, is sensitive to ambient fields generated by nearby electronic equipment. Identifying this effect was essential for validating the need for shielding and for interpreting measurement uncertainties in controlled experiments.

Application Testing using the MQTT Protocol

With the Arduino-ESP32 synchronization validated and the ESP32 fully integrated with the MQTT protocol, we were able to assess the system's remote-monitoring performance. MQTT was selected because its lightweight publish-subscribe architecture minimizes bandwidth usage and ensures reliable transmission even under unstable network conditions - an essential requirement for real-time energy monitoring from anywhere in the world (Sasaki & Yokotani, 2019; Silva et al., 2021).

To evaluate data delivery - from sensor acquisition to user-level visualization - the developed system used the ON OFF iOS application as the MQTT client. This platform allowed us to verify whether the ESP32, acting as the publisher, could consistently deliver data to an external broker and whether the client could retrieve and display measurements without loss, delay, or formatting inconsistencies.

For testing purposes, only the measurement from the main circuit breaker (total current of the installation) was published during testing. Focusing on a single channel simplified the validation of communication robustness, eliminating internal confounding factors. This ensured that any observed latency or discrepancy originated from the network path - not from the sensing chain.

This link contains an MQTT video test: https://docs.google.com/presentation/d/1d3qZIVl55eJ1PHWbBPnyKwMF6CbK8FIfDjc_fjMUi6Q/edit?usp=sharing

Web Interface Testing

A web server was implemented on the ESP32 so that consumption data can be accessed remotely via a standard HTTP interface. This allows users to monitor energy usage in real time from any browser on the network. This dual-interface strategy – MQTT and HTTP - was implemented not as an additional feature, but as a test of system robustness and flexibility. By verifying that the ESP32 could simultaneously handle data reception from the Arduino, local processing, and HTTP-based data delivery, we assessed whether the overall architecture could support heterogeneous user environments - ranging from lightweight IoT dashboards to conventional browser-based access.

The code is available at the following github repository: https://github.com/Peagudoo/Monitoring-Project-Code/blob/main/WebServer_test_code

Test video with the web server: https://docs.google.com/presentation/d/1n3twGLn_ofM23tX9RS8k1i5nGzYXelZxA8VGZgHaPw0/edit?usp=sharing

Results

An analysis of the margin of error for various electrical appliances was conducted and then compiled into Table 1. Additionally, a comparative graph between the clamp-on current sensor and the clamp ammeter was created, as shown in Figure 14, and a correlation plot in Figure 15, illustrating how the measurement error varies with the current measured by the SCT-013.

Nº	Devices	SCT-013 (A)	Professional clamp ammeter (A)	Deviation	Margin of Error	N (measurements taken)	SD (A)
1	Sterilair Air Purifier	0.26	0.25	0.01	4%	5	0.009
2	LG SmartTV	0.62	0.65	-0.02	-5%	5	0.012
3	Arno Fan (low power)	0.64	0.65	-0.01	-2%	5	0.011
4	Arno Fan (medium power)	0.82	0.82	0.00	0%	5	0.012
5	Arno Fan (high power)	1.07	1.08	-0.01	-1%	5	0.013
6	Blender (low power)	1.44	1.46	-0.02	-1%	5	0.015
7	Consul Refrigerator	1.60	1.63	-0.03	-2%	5	0.016
8	Blender (high power)	1.74	1.75	-0.01	-1%	5	0.016
9	Philco Vacuum cleaner	3.32	3.33	-0.01	0%	5	0.021

10	Conair Hair Dryer (low power)	3.45	3.50	-0.05	-1%	5	0.020
11	Philco Hair Dryer (high power)	4.35	4.38	-0.03	-1%	5	0.020
12	Conair Hair Dryer (high power)	6.22	6.30	-0.08	-1%	5	0.021
13	Philco Hair Dryer (high power)	8.20	8.40	-0.20	-2%	5	0.022
14	Cadence Electric Kettle	8.31	8.46	-0.15	-2%	5	0.022
15	Microwave Oven	12.14	12.70	-0.56	-4%	5	0.025

Table 01 - Comparative table with data collected from SCT-013 and professional clamp ammeter.
Source - AUTHORS

The average margin of error is at most ±5%.

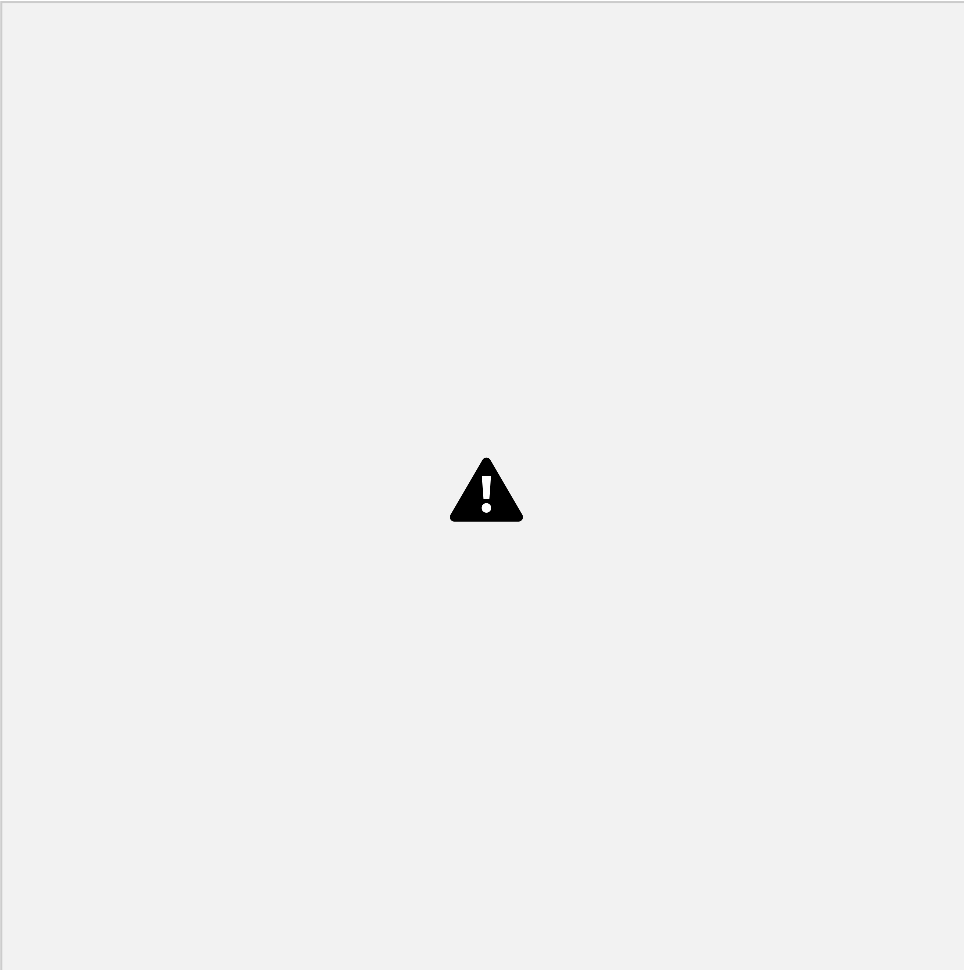


Figure 14 - Comparative graph between data read by the SCT-013 sensor and the professional clamp ammeter.
Source - AUTHORS

As summarized in Table 1 and Figure 14, the SCT-013 readings agreed with the reference meter within ±5% for all tested appliances. The average error was around 1-2%, with small standard deviations, indicating consistent performance. These results confirm that the SCT-013 provides sufficient accuracy for low-cost monitoring applications.

To ensure statistical validity, each measurement was repeated five times (N = 5) for each tested load. The SCT-013 showed high repeatability, with standard deviations typically below 0.025 A. The table reports both the mean error relative to the clamp ammeter and the corresponding standard deviation across repetitions.

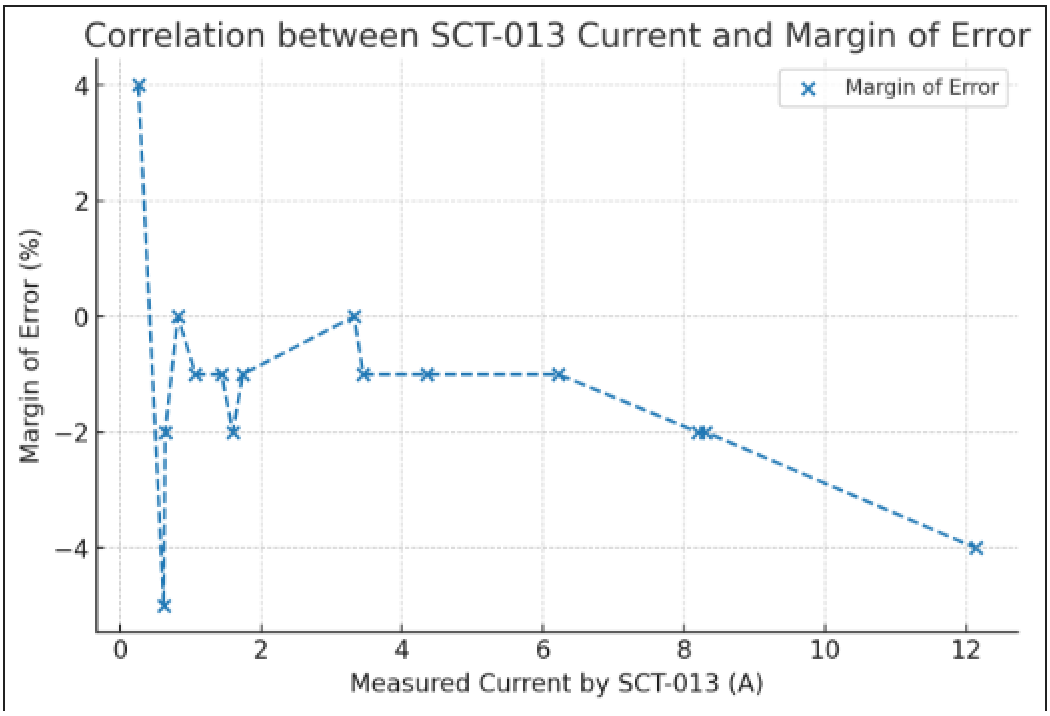


Figure 15 - Correlation graph between measured current and margin of error.
Source - AUTHORS

Figure 15 demonstrates that at low currents the relative error is high compared to medium currents (2 - 6 A). This phenomenon is consistent with the sensor's fixed offset and the ADC quantization effect (explained in the next session).

Uncertainty Budget

The accuracy of the measurements obtained with the prototype depends on the combined performance of the sensing element, conditioning circuit, and analog-to-digital conversion stage. To assess the system's reliability, an uncertainty budget was established based on repeated laboratory tests under controlled environmental conditions. The main uncertainty contributors identified were the burden resistor characteristics, the ADC performance of the microcontroller, and the linearity of the SCT-013 current transformer.

Temperature Drift of the Burden Resistor

To characterize additional effects not included in the initial estimate, supplementary experiments were conducted to evaluate thermal drift of the burden resistor. During operation, the 33 Ω resistor dissipated approximately 0.165 W at nominal load (secondary current 70.7 mA), leading to an average temperature rise of 17 °C after 15 minutes of continuous use. Resistance increased by 0.09 Ω (0.27%), consistent with theoretical predictions for a metal-film resistor with a 50 ppm $°C^{-1}$

temperature coefficient. Under an overload condition corresponding to double the nominal current, the power dissipation reached 0.66 W and the temperature rose by 35 °C, resulting in a resistance variation of 0.19 Ω (0.58%).

Although this drift produces only minor deviations in the measured current, it represents a relevant contribution to the overall uncertainty, particularly under sustained or high-load operation. For the present prototype, the temperature-related contribution is estimated at ±0.3% under normal conditions and up to ±0.6% under overload. These results demonstrate that thermal effects remain small compared with the dominant linearity and tolerance components but are measurable and should be included in future calibration analyses.

ADC Non-linearity and Combined Effects

(Adamo et al., 2007; Zhengbing et al., 2015) The analog-to-digital conversion represents an additional source of systematic uncertainty. The Arduino's 10-bit ADC (ATmega328P) converts analog voltages into discrete digital steps of approximately 4.88 mV per level, known as the Least Significant Bit (LSB). Its Integral Non-Linearity (INL) - the deviation between the actual and ideal conversion curve - is approximately ±2 LSB, according to the manufacturer's datasheet. The ESP32, responsible for wireless data transmission, employs a 12-bit ADC with an INL of up to ±12 LSB depending on the channel. Experimental evaluation using a calibrated 1.000 V RMS sine wave revealed deviations of ±0.4% for the Arduino and ±0.7% for the ESP32, values consistent with these specifications.

Because the Arduino is responsible for primary signal acquisition, a conservative ±0.5% ADC uncertainty was incorporated into the budget. Temperature drift and ADC non-linearity can interact, since a small rise in burden resistor voltage increases the analog input level, slightly amplifying non-linear distortion at higher ADC codes.

Combined Uncertainty and Outlook

The burden resistor (33 Ω, ±5% tolerance) and the voltage divider resistors (10 kΩ, ±1% tolerance) introduce a proportional scaling uncertainty. The Arduino ADC, with 10-bit resolution (≈4.88 mV/step over 5 V) and a typical nonlinearity of ±0.5 LSB (ATmega328P), adds quantization and transfer-curve error (Adamo et al., 2007; Zhengbing et al., 2015). The SCT-013 datasheet specifies linearity deviations up to ±3% across its nominal range. Using the root-sum-square (RSS) method, the combined type-B uncertainty is estimated at 6%, which aligns with the maximum experimental deviation observed (5%). Random errors, evaluated through repeated measurements, were comparatively small (standard deviation <0.02 A in most cases).

$$u_c = \sqrt{(5.0\%)^2 + (1.0\%)^2 + (1.0\%)^2 + (3.0\%)^2 + (0.5\%)^2 + (0.3\%)^2} = 6.02\%$$

Hence, these factors may influence accuracy in long-duration or high-temperature environments and are identified as priorities for future investigation.

Project Costs

A cost analysis of the project was conducted for potential commercial application, as seen in Table 02, and it is noted that the total cost differs from that of developing the prototype. It is important to consider that the shopping was made in Brazil, and the total cost may vary for different countries.

Installation Type	Total Cost (R$)	Total Cost (US$)	Notes
User's commercial installation	R$ 223.47	US$ 40.14	Cost of the installation used by the user.
Experimental Panel for testing	R$ 579.93	US$ 104.15	Constructed by the research team to simulate a house electrical panel for experiments.

Table 02 - Complete project cost table.
Source - AUTHORS

Limitations

As previously noted, the project initially aimed to rely solely on the ESP32 for sensor signal conversion and MQTT data transmission. However, even after recalculating the load resistor for its 3.3 V ADC, the resulting measurements showed insufficient accuracy.

R = V (analog input / 2) / I (sensor) = 1.65 V / 0.0707 A = 23.33 Ω.

The closest commercially available resistor to the calculated value is 22 Ω.

CalibrationValue = number of turns of the sensor/ value of load resistor

CalibrationValue = 2000 / 22

CalibrationValue = 90.909

Therefore, the sensor initialization should include the newly calculated calibration value.

```
SCT013.current(pinSCT, 90.909);
```

Even with the correct calibration values and burden resistor configuration, inaccurate measurements were being obtained when using the ESP32 alone. Measured values were off by more than 50%, and data was collected even without current passing through the SCT-013.

This discrepancy is partly attributed to the characteristics of its internal analog-to-digital converter (ADC), which is not well suited for low-level, biased analog signals such as those produced by the SCT-013. The ESP32 ADC typically exhibits a voltage offset of approximately 0.17 V, meaning that conversions do not start at 0 V even in the absence of input (Maier et al., 2017). In addition, the ADC suffers from integral nonlinearity, channel-dependent gain variation, and sensitivity to input impedance and stability (Adamo et al., 2007; Zhengbing et al., 2015). The SCT-013 output, after passing through the burden resistor and midpoint bias network, has relatively high impedance, which can lead to unstable sampling when directly connected to the ESP32. Small bias fluctuations can cause the ADC reference node to drift, leading to noisy or inconsistent readings, and a single calibration constant becomes unreliable across different load levels. However, with an appropriately low-impedance conditioning stage and the use of an external high-linearity ADC - such as the ADS1115 - the instability can be significantly mitigated or even eliminated. In such a configuration, the ESP32 could operate as the sole microcontroller: the SCT-013 signal would be conditioned to properly drive the external ADC, which in turn would provide stable and linear digital readings to the ESP32 via I²C. In contrast, the Arduino's 10-bit ADC, though simpler, maintains a more linear and predictable transfer function over its input range, resulting in more stable and reproducible current measurements (Thakare et al., 2016). As the project is an early prototype and relies on easy and accessible approaches, it was performed acquisition and analog processing on the Arduino (which exhibited more linear ADC behavior); after synchronizing the Arduino with the ESP32, the ESP32 receives the processed data and publishes it to the MQTT broker, from which the application subscribes to topics and acts as a client (Sasaki & Yokotani, 2019; Silva et al., 2021).

Another important factor to consider is that the external environment slightly affects the results collected by the sensor. For example, when the sensor is not measuring current from a conductor wire, it may still register magnetic fields emitted by nearby electronic devices. However, when there is an active current flow in the conductor, the sensor ignores this external interference and measures only the data from the intended device.

.

Conclusion

Project Conclusion

In general, the group concludes that the electric energy monitoring project successfully achieved its main objectives, demonstrating it to be an effective low-cost, modular, and accessible system capable of promoting awareness about energy consumption - the system has an accuracy of approximately 95%. This level of performance places the system within the lower bound of commercial clamp-meter solutions - typically rated between ±1% and ±3% - while remaining significantly more accessible in cost and implementation complexity. By employing a clamp-on current sensor and technologies such as Arduino, ESP32, and the MQTT protocol, it became possible to monitor energy consumption in real time from anywhere with an internet connection, thereby helping to reduce waste and encouraging more responsible electricity use (Sasaki & Yokotani, 2019; Silva et al., 2021; Tamkittikhun et al., 2015; Thakare et al., 2016).

Furthermore, from a socio-economic perspective, the project holds crucial importance as it addresses a global issue: the efficiency in electrical energy use. By monitoring energy expenditure, users can identify major points of waste and adopt more effective measures to optimize consumption. In Brazil, where electricity costs can represent a significant burden on household budgets, especially for low-income families, this technology has the potential to generate a profound positive impact. Companies and other sectors that adopt this solution can also achieve greater energy efficiency, which translates into financial savings and enhances their market competitiveness (Bento, 2024; Emanoel, 2023).

However, like any project, our system has its advantages and drawbacks. Among its main advantages, accessibility stands out, as the project can be used by diverse audiences given that the materials employed have an affordable cost, evinced by Table 02. Additionally, safety is a strong point, since the use of the SCT-013 sensor avoids the need to directly interfere with electrical wiring, facilitating installation and eliminating the risk of electric shocks. Another important aspect is innovation, since the solution enables remote and real-time monitoring of energy consumption through the integration of the ESP32 with the MQTT protocol, allowing consumption tracking from anywhere in the world (Sasaki & Yokotani, 2019; Silva et al., 2021).

On the other hand, the project presents some drawbacks, such as dependence on a stable internet connection, since remote monitoring relies on a constant internet connection for data to be transmitted correctly. In locations with limited network infrastructure, the system's effectiveness may be compromised. Another shortcoming is the absence of an alert system, as the current system does not issue notifications when energy consumption exceeds certain thresholds. Moreover, the project did not implement cloud-based analysis, active response due to the high demand of energy, and multi-channel measurement which is highly recommended for applications in complex industrial systems.

A broader reflection emerging from this work concerns the inherent trade-offs that characterize low-cost IoT sensing prototypes. The choice to pair the SCT-013 with the Arduino - rather than relying solely on the ESP32's internal ADC - illustrates a common engineering compromise between measurement accuracy, component cost, and system scalability. While the Arduino's simpler and more linear ADC offered greater stability and reproducibility for the purposes of this prototype, it also introduced additional hardware complexity and limited the potential for integration into more compact or higher-channel-count designs. Conversely, although the ESP32 provides superior processing capabilities and native wireless connectivity at a low price point, its ADC nonlinearity and impedance sensitivity constrain its use for precision analog acquisition without external conditioning. This project therefore highlights how practical IoT development often requires balancing these competing priorities rather than optimizing a single parameter in isolation.

Safety and Ethics

The system interfaces with dangerous mains voltage, so industry-standard safety measures are required. All high-voltage conductors are properly insulated and enclosed to prevent accidental contact. A suitably rated fuse is placed in series with each monitored conductor to protect against overloads. Clearance distances and insulation of materials comply with relevant electrical standards. The SCT-013 sensor provides galvanic isolation, but care is taken in circuit layout and wiring to maintain safety. On the ethical side, the device reports only aggregated energy use, not personal information, so privacy impact is minimal. Users should still be informed that their consumption data is collected and transmitted remotely, but no sensitive personal data (e.g. identities or usage patterns per person) are exposed. It is important to note that the SCT-013 must be clamped around just one single phase conductor, otherwise it reads opposed magnetic fields that cancel each other.

Future Implementations

For readers reproducing this work, it is recommended expanding reliability and usability in low-infrastructure contexts while preserving the system's low-cost nature. Although the current prototype already provides full offline functionality through real-time LCD visualization, future versions may incorporate non-volatile local memory (e.g., EEPROM, FRAM, or SD-card logging) to enable autonomous long-term data storage, with delayed synchronization when intermittent connectivity becomes available. To improve measurement accuracy, users reproducing the system may employ the Arduino ADC or adopt external high-linearity converters such as the ADS1115, or use an op-amp buffer; alternatively, calibration tables and oversampling techniques can be applied directly to the ESP32 to compensate for its nonlinearity and 0.17 V offset.

Additionally, since the microcontrollers support deep-sleep and periodic sampling modes, the system can operate with substantially reduced energy consumption, enabling future iterations to adopt non-intrusive powering strategies based on inductive or magnetically coupled energy-harvesting modules. Further enhancements include applying electromagnetic shielding to minimize external interference, implementing threshold-based alert systems, adding cloud-based analytics when available, and exploring AI-assisted consumption prediction and insights. These improvements would make the platform more resilient, scalable, and informative across diverse real-world environments.

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We thank the reviewer for the detailed and technically rigorous feedback, which has contributed substantially to improving the precision and clarity of the manuscript. We carefully addressed each of the concerns raised. The resulting version is more technically accurate, more conceptually rigorous, and better positioned for scholarly contribution.

Remote Energy Monitoring via MQTT and SCT-013: A Prototype for Scalable IoT Systems

Second Review of Reviewer 1

The introduction has been much improved. More clear and interesting detail about weather patterns in Brazil have been included. Less relevant basic derivations have been removed.

I'm still troubled by the use "non-invasive", it's imprecise and gives the mistaken impression that the measurement device doesn't affect the main circuit. In fact you go further and say in line 97 that it doesn't affect the grid.

Line 97:

"The system utilizes the non-invasive (no interference in the electrical grid) current sensor SCT-013 that measures the magnetic field variation around a conductive wire and converts this data into a current proportional to the original."

I suggest removing the term "non-invasive" and instead just say the system is "magnetically coupled". The bracketed claim "(no interference in the electrical grid)" is wrong. The measurement does directly affect the main circuit in a number of ways beyond the scope of this paper. The effect may not be significant in terms of power usage, but it's important to be precise in language.

Regarding the terminology in line 97, we fully agree that the expression “non-invasive” was imprecise and could suggest that the measurement process has no effect on the primary circuit. Following the reviewer’s recommendation, we removed the term and replaced it with “clamp-on” or “magnetically coupled,” depending on the sentence, while also eliminating the parenthetical “no interference in the electrical grid.” This correction increases conceptual accuracy and aligns the manuscript with accepted electrical engineering terminology.

The author is correct in their choice of 33 Ohm and justification... good.

On line 135. Incorrect Maxwell's equation. It's the EMF or Voltage which is equal to -d_Phi/dt. It's the integral around a loop of the electric field being equal to the area integral of the changing magnetic field. In short, just change "E" which represents electric field to either "V" or "EMF".

We corrected the equation accordingly by substituting E with V (or EMF), ensuring consistency with electromagnetic theory.

Regarding using an Arduino AND an ESP32 due to the inaccurate response of the ESP32 ADC. At first I was surprised by this. It is true that the ESP32 can give offset voltages and the response can be non-linear. However, these problems can be mitigated in two ways, first careful choice of input impedance, second, by calibrating the response with a known device. I'm not suggesting this be done now. However, the author could note that their current device is an early prototype, and using these methods, the system could run without the Arduino.

We appreciate the reviewer's insightful comments concerning the ESP32's ADC limitations. In response, we clarified in the manuscript that the observed discrepancies are not solely attributable to the ESP32 ADC itself, but rather to a combination of nonlinearity, offset behavior, and sensitivity to input impedance - factors that can indeed be mitigated with proper design choices: the system may employ the Arduino ADC or adopt external high-linearity converters such as the ADS1115, or use an op-amp buffer; alternatively, calibration tables and oversampling techniques can be applied directly to the ESP32 to compensate for its nonlinearity and 0.17 V offset.

"The switched-mode power supply was used only in the laboratory setup to ensure consistent operation during extended testing. In practical applications, the system can be powered by a 6.5 V DC adapter or battery pack. Therefore, a nota was inserted with this explanation in Prototype Development session. While inductive energy harvesting is conceptually possible, the current generated by the SCT-013 secondary (typically below 70 mA) is insufficient to sustain a microcontroller (typically 500 mA). "

Important correction. Speaking just in terms of current draw, 500 mA is really high. I assume it includes both the ESP32, Arduino, and all peripherals. Microcontrollers when used skilfully can be programmed with interrupts such that they make a measurement, drawing perhaps 50 mA for maybe 0.1ms, then they can go into low-power mode in which they'll draw micro-amps. Same for both the ESP32 and the Arduino. The brings the average power usage down enormously, perhaps to the range of several mA. A 500 mA instantaneous draw from any individual microcontroller is unrealistically high and points to design problems. If it's from the whole circuit including peripherals then OK. However, you don't need to monitor the voltage at the highest sample rate of the Arduino. Recording and sending a reading or a few average readings every 10s is probably sufficient. For the rest of the time both microcontrollers can be in low power mode drawing less than 1 mA. I'm not suggesting you change your design or do new experiments. But it may be worth noting that these low power features should be included in subsequent prototypes.

What's more. You mention using a battery. Phone batteries are high quality, yet using this kind of battery your battery would need a complete recharge after around 6 hours. This is clearly not a solution.

It is possible to magnetically couple energy from the power line to power your device, independent of the SCT-013, or as you say, to use a 6.5 V DC adaptor, however, the bigger issue is the energy efficiency.

We now explicitly state that the supply was used only in the laboratory for stable operation and that practical deployments may use a 6.5 V adapter or a battery pack just for short-term measurements. The revised manuscript clarifies that a battery-only configuration is unsuitable for long-term operation without implementing low-power features. We also revised the earlier statement about current consumption (500mA). In its place, we explain - following the reviewer's guidance - that instantaneous microcontroller draw is typically far lower, and that both Arduino and ESP32 support deep-sleep modes with microamp consumption between sampling cycles. We additionally highlight that the system could be redesigned to operate on interval-based sampling, significantly reducing average current and enabling the use of magnetically coupled energy-harvesting modules (independent of the SCT-013). This refinement has been integrated into the Future Implementations section, noting that these low-power strategies are appropriate for subsequent prototypes.

I recommend the paper be accepted for publication once these points have been addressed in the manuscript.

We would like to express our sincere appreciation for the reviewer's thoughtful and constructive feedback. Each of the points raised contributed meaningfully to strengthening the clarity, coherence, and scholarly positioning of our manuscript. In revising the paper, we worked carefully to incorporate every suggestion, ensuring that both the technical and socio-technical dimensions of the project were more clearly articulated.

Second review report: Remote Energy Monitoring via MQTT and SCT-013: A Single-Channel Prototype for IoT System

Decision: Accepted with minor revisions

The authors have made substantial and thoughtful revisions, significantly strengthening the manuscript. The addition of detailed uncertainty analysis, cost evaluation, ethical considerations, and a more critical discussion of limitations greatly enhances the paper's rigor and relevance. The revised manuscript demonstrates marked improvement in technical clarity and scholarly framing. However, the following constructive points may further elevate its impact:

Review Details:

1. Sharpening the Abstract and Introduction/Literature Review

The abstract remains somewhat descriptive and could be more forcefully framed. Consider restructuring it to: (a) contextualize the energy monitoring challenge, (b) state the paper's unique contribution: a low-cost, non-invasive prototype using open-source hardware, (c) summarize key methodological innovations (e.g., Arduino-ESP32 synergy, MQTT integration), and (d) highlight practical implications, such as alignment with SDG 7. The introduction should avoid repeating the abstract and instead build a clearer narrative arc from global energy challenges to the prototype's specific relevance in contexts like Brazil. In addition, transform the Literature Review from a summary into a justification, the sections can sometimes read like a "lab notebook" or "build manual", as showing a sequential account of what was done, rather than a structured argument.

Regarding the first comment, we agree that the abstract was previously descriptive and did not fully convey the significance of the research. We therefore restructured it to foreground the global challenge of affordable energy monitoring, present the originality of our low-cost, non-intrusive prototype, and highlight the methodological contributions—particularly the Arduino–ESP32 hybrid acquisition chain and the use of MQTT for remote access. We also clarified its practical implications, including alignment with SDG 7 and specific relevance to energy affordability in Brazil. The Introduction was rewritten to avoid repeating the abstract and now develops a clearer narrative progression from international energy challenges to the limitations of existing solutions and the resulting motivation for our prototype. The Literature Review was significantly refined as well: descriptive and step-wise explanations resembling a lab manual were removed, and the sections now justify each design choice conceptually. Rather than recounting assembly procedures, the review now connects the chosen technologies to the research problem, strengthening its argumentative structure.

2. Clarifying the Central Argument on Sensor Limitations

While the limitations of the ESP32's ADC are well discussed, the paper could more explicitly synthesize how this design trade-off exemplifies a broader theme in IoT prototyping: balancing accuracy, cost, and scalability. A dedicated paragraph in the Limitations or Conclusion section could reflect on how such compromises inform future iterations or similar low-cost sensing projects.

Concerning the second comment, we agree that the discussion of the ESP32 ADC needed to be more explicitly linked to a broader engineering trade-off. We added a synthesizing paragraph in both the Limitations and Conclusion sections clarifying that the difficulty with the ESP32's ADC exemplifies a common challenge in low-cost IoT prototyping: balancing accuracy, component cost, ease of integration, and scalability. This framing reinforces the idea that the Arduino–ESP32 pairing was not merely a workaround, but an instructive design compromise with relevance for other systems facing similar constraints.

3. Strengthening the Socio-Technical Synthesis

The manuscript effectively highlights the prototype’s technical performance but could better integrate socio-technical insights. For instance, how might the design be adapted for underserved communities with limited internet access? A brief discussion on offline functionality or data caching strategies would enrich the Future Implementations section and reinforce the inclusive aims of the project.

We expanded the Future Implementations section to address deployment in underserved communities or environments with inconsistent network infrastructure. This now includes a discussion of offline functionality through non-volatile memory (EEPROM, FRAM or SD-card), intermittent-connectivity synchronization, and low-power measurement strategies. We also mention the possibility of adopting magnetically coupled energy-harvesting modules to reduce reliance on external power. These additions highlight the inclusive design implications of the system and reinforce its relevance beyond purely technical performance.

4. Reframe the Methodology from "What We Did" to "How We Ensured Validity"

The current structure is a bit procedural. Weave a narrative of problem-solving and validation.
For example, introduce the Arduino/ESP32 section not just as a description about what has been done, but how design to be considered as a solution to a problem.

We fully agree with the concern about the Methodology reading as procedural. We revised this section extensively so that it now emphasizes objectivity and validation rather than narrating each step taken. For example, the Arduino/ESP32 section was rewritten to frame the dual-microcontroller architecture as a response to the ESP32’s ADC limitations, rather than a chronological account of implementation. Similarly, descriptions of the experimental setup now focus on how each configuration allowed us to test accuracy, isolate interference, or validate system robustness. This reframing shifts the tone from “what we built” to “how we justified and validated our design choices.”

5. Refining Language for Academic Precision

Some phrasing remains slightly informal (e.g., dramatically off, great accomplishment). Replace these with measured academic language (e.g.,significant discrepancies were observed, represents a promising initial result). Additionally, the Conclusion could more explicitly reiterate how the prototype’s ±5% accuracy and modular design compare with commercial alternatives, reinforcing its practical and scholarly contribution.

Informal terms were replaced with academically appropriate phrasing, ensuring tone consistency throughout the manuscript. The Conclusion was strengthened by explicitly comparing the prototype’s 95% accuracy and modular architecture with the characteristics of commercial alternatives (97-99% accuracy) , thereby reinforcing the contribution of our system both in academic and practical terms.