Wattcher: A Centralized Electrical Energy Monitoring and Control System with Lan Connectivity

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ABSTRACT

As energy consumption in large facilities such as schools and offices increases, the need for efficient energy monitoring and control has become critical. This study presents an Arduino-based Energy Monitoring and Control System designed to help facility managers detect and reduce unnecessary power usage, especially outside of operational hours. The system used three PZEM-004T modules to measure voltage, current, power, and energy across three branches in a panel board, with data transmitted via Ethernet and stored in a cloud database. An external contactor was added to demonstrate the potential for remote control, though no existing panel wirings were modified. The study aimed to (a) monitor real-time energy data using non-invasive sensors, (b) demonstrate remote appliance control, and (c) compare readings from current transformers (CTs) with those from a standard clamp meter to assess accuracy. Results showed consistent voltage and power measurements, with average values of 703.6 W, 73.5 W, and 2241.4 W for the three monitored branches. A paired t-test comparing CT readings to clamp meter readings yielded $t(1) = 19.25$, $p < 0.05$, indicating a statistically significant difference in current values, primarily due to calibration variance. Despite this, trends remained consistent across both instruments. The system demonstrated effective real-time monitoring and the potential for scalable deployment, with future improvements targeting calibration, accuracy, and broader coverage.

Keywords: Energy Monitoring, IoT, Arduino, Current Transformer, Contactor, Remote Control

INTRODUCTION

Energy consumption remains a critical global issue with far-reaching economic and environmental impacts. According to the International Energy Agency (2020), global energy demand rose by 2.3%—the fastest rate in a decade—driven by increased electricity use in countries such as China and the United States, due to industrial growth and extreme weather. Similarly, the Philippines has experienced a steady annual increase in electricity demand, averaging 5.6% over the past decade (Department of Energy, 2021). This rising consumption, combined with aging infrastructure and peak-period shortages reported by NGCP, underscores the urgent need for efficient energy management systems.

Institutions such as schools, offices, and other large facilities often struggle to manage energy use effectively, largely because of the lack of accessible monitoring tools. Energy monitoring systems, particularly those based on Arduino microcontrollers, offer a promising solution by providing real-time data collection and analysis. Khaleel et al. (2024) emphasized the role of such systems in allowing users to view energy consumption remotely, analyze patterns, and control equipment. Central to this setup are current transformers (CTs), which, as Schneider Electric (2020) noted, are capable of accurately measuring current without interrupting circuits.

By integrating CTs with Arduino boards, institutions can continuously monitor electricity usage across multiple circuits. This setup enables the detection of peak loads, unusual consumption, and potential inefficiencies. Sharma and Patel (2020) noted that sensor-based systems offer accurate and efficient energy tracking, making them suitable even in industrial settings. Moreover, data analytics further enhances these systems by identifying trends, forecasting usage, and supporting energy-saving decisions (Zhao et al., 2021; Hossain et al., 2021).

Beyond basic monitoring, these systems can be connected to building management platforms, enabling centralized energy oversight and control (Jin et al., 2020). Alerts for anomalies or maintenance needs make them proactive tools for operational efficiency (McKenna et al., 2020). For institutions like schools, which often operate on limited budgets, implementing such technologies provides a sustainable way to manage energy more responsibly while reducing costs (Lee & Kim, 2021).

In summary, as energy demand continues to rise globally and locally, Arduino-based energy monitoring systems offer an effective, low-cost, and scalable solution. Through accurate measurements, real-time tracking, and data-driven insights, these systems empower institutions to make informed decisions that support both operational efficiency and environmental sustainability.

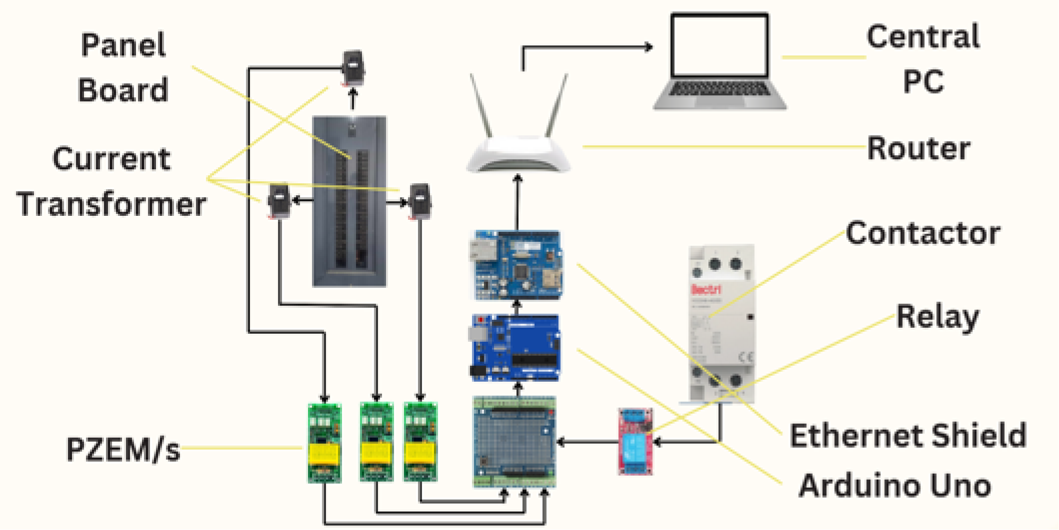
METHODOLOGY

A. Research Design

Hardware Design

Figure 1

Overall System Architecture of Wattcher



Conceptual Framework

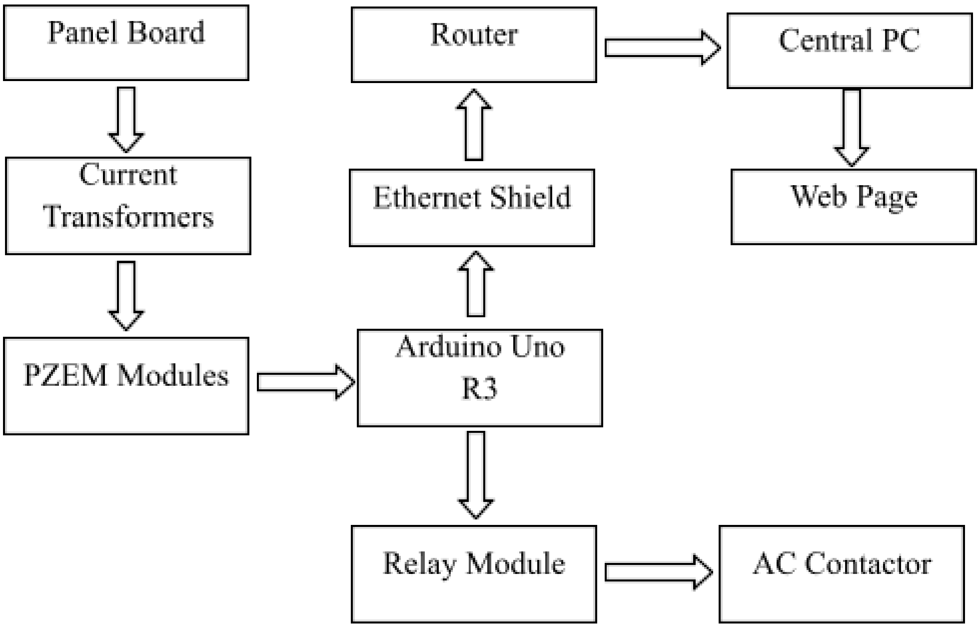
The conceptual framework of this study centers on integrating Arduino microcontrollers with current transformers (CTs) to establish a reliable, real-time energy monitoring and control system. The CTs measure vital electrical parameters, such as voltage, current, power, and energy. These measurements are transmitted to Arduino microcontrollers, which process the data and relay it to a central monitoring station via Ethernet.

The central monitoring and control station serves as the system's analytical hub. Here, the processed data is visualized through a dynamic web interface, providing users with an intuitive overview of their energy usage. The system continuously updates and displays real-time readings, allowing users to identify consumption patterns, detect inefficiencies, and recognize irregularities in energy behavior.

This integration of sensing, embedded control, and web-based visualization creates a comprehensive and interactive energy management solution. It empowers users to make informed decisions, take corrective actions, and implement strategies for optimizing power consumption. Ultimately, this framework supports improved energy efficiency, sustainability, and cost-effectiveness—especially in large-scale or multi-zone establishments.

The block diagram in Figure 2 illustrates the overall hardware architecture of the Wattcher energy monitoring system. It shows the integration of key components responsible for data acquisition, processing, communication, and control.

Figure 2
Block Diagram of Wattcher



The hardware design of the Wattcher system includes the following components:

- Current Transformers (CTs): These devices measure the current flowing through electrical circuits. They are selected based on their accuracy, range, and compatibility with the building's electrical system.
- PZEM Modules: These modules measure electrical parameters like voltage, current, power, and energy. They simplify the process of integrating energy monitoring with the Arduino system.
- Contactors: These are electromechanical switches used to control high-power circuits, enabling safe and remote switching of loads in energy monitoring systems.
- Relay Module: An interface board that allows microcontrollers to control high-voltage devices by using low-voltage digital signals.
- Arduino Uno: This microcontroller serves as the central processing unit, programmed to read data from sensors and manage data transmission.

- DIN Rail Mount Screw Terminal Block Adapter Module: This module provides a convenient way to connect and organize wiring for the Arduino and other components, ensuring secure and reliable connections.
- Arduino Ethernet Shield: This shield enables the Arduino Uno to connect to a network using Ethernet, facilitating data transmission to a centralized server.
- Central PC: This computer serves as the centralized monitoring station, receiving and analyzing data from the Arduino-based energy monitoring system.

The hardware setup involves connecting CTs and voltage sensors to the Arduino microcontrollers, which process and transmit the data through an Ethernet connection. The system's design ensures accurate and reliable data collection, necessary for effective energy monitoring.

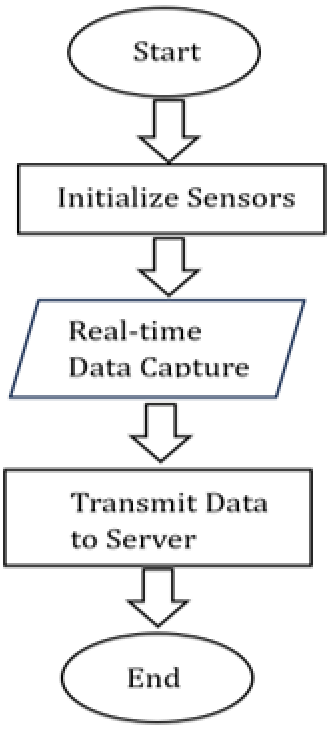
Software Design

The software component of the Wattcher system governs sensor initialization, data collection, and communication with the server. The flowchart below outlines the core processes involved in capturing real-time energy data and transmitting it for monitoring and analysis.

The software design involves several key components:

Figure 3

Software Architecture of Wattcher



- Arduino Programming: The microcontrollers are programmed using the Arduino IDE to read sensor data, process it, and transmit it to a central server.
- Data Processing Algorithms: The collected data is processed using algorithms to compute energy consumption and identify usage patterns.
- Data Transmission: The software includes protocols for transmitting data over Ethernet cables to ensure reliable and secure data transfer.

- Data Storage and Analysis: The transmitted data is stored in a central database, where it can be analyzed using software tools to generate reports and insights.

B. Research Locale

The research was conducted within the TTBDO Building of Saint Mary's University (SMU) in Bayombong, Nueva Vizcaya. This location was selected for its accessibility and relevance, as the monitoring system will provide valuable insights into the building's energy consumption patterns, aiding energy conservation efforts.

C. Research Participants

The participants in this study included facility managers, maintenance personnel, and possibly occupants of the TTBDO Building. The selection criteria focused on individuals directly involved in the building's operation and maintenance, ensuring they can provide relevant insights and feedback. Demographic information, such as job role and experience level, were collected to understand the diversity of perspectives.

D. Research Instruments

Throughout the study, the complete prototype served as the main research tool, incorporating essential components such as current transformers (CTs), PZEM modules, Arduino Uno microcontrollers, relay modules, contactors, DIN rail mount screw terminal block adapter modules, Arduino Ethernet shields, a router, and a central PC. Supplementary tools, such as a multimeter/clamp meter and a laptop, were also used by the researchers to gather and compare data from the prototype. These instruments and tools were critical in ensuring accurate data collection, reliable performance, and effective analysis of the energy monitoring and control system in the TTBDO Building at Saint Mary's University (SMU).

E. Data Gathering Procedures

The initial step in data gathering was installing the energy monitoring and control system within the TTBDO building of Saint Mary’s University. This site was selected for its multiple electrical loads, structured panel boards, and active energy use across various departments, making it an ideal environment for evaluating the system’s performance and utility. The facility provided a realistic setting to assess how effectively the system captures data under normal operational conditions.

The Arduino-based energy monitoring systems, integrated with current transformers (CTs), were installed and clamped onto designated circuit lines in the building’s panel boards. These placements were strategically chosen to isolate and monitor separate load branches, ensuring comprehensive and accurate tracking of electrical consumption behaviors.

Once deployed, the system continuously captured real-time energy data, including voltage, current, active power, and load fluctuations. The Arduino microcontrollers processed this information and transmitted it through a local area network (LAN) to a centralized monitoring dashboard for aggregation and real-time viewing.

All collected data was logged and stored in a structured format for further statistical analysis and validation. Monitoring took place over an extended period—spanning both active operational hours and off-peak times—to ensure the reliability, consistency, and repeatability of the system’s measurements. Additionally, timestamps and identification tags were assigned to each data stream to aid in segmenting and interpreting usage trends. Regular backups were performed to safeguard against any data loss during the observation process.

Hardware Development

Pre-Installation Component Testing and Validation

Before proceeding with the installation of the energy monitoring components, the researchers first ensured that all modules and instruments were functional and accurate. This step was crucial to avoid unnecessary troubleshooting during deployment and to establish confidence in the integrity of the monitoring system.

The PZEM-004T v3.0 energy meter was connected to the Arduino Nano using appropriate RX and TX pins, with the CT sensor attached to a test wire carrying a small load. Serial communication was established between the Arduino Nano and the PC via USB to verify data transmission.

Figure 4
Initial Connection setup of PZEM-004T with Arduino Nano

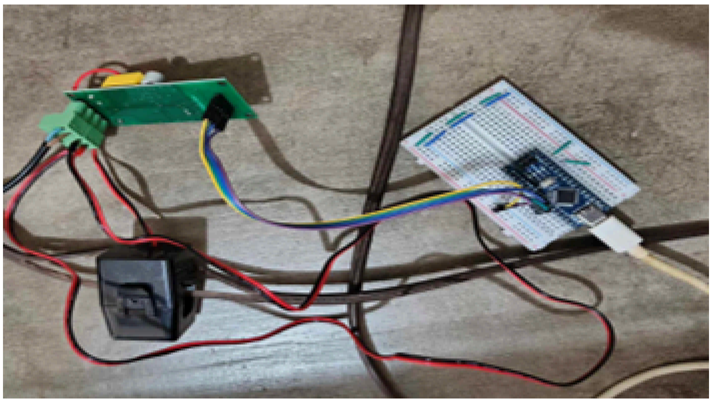
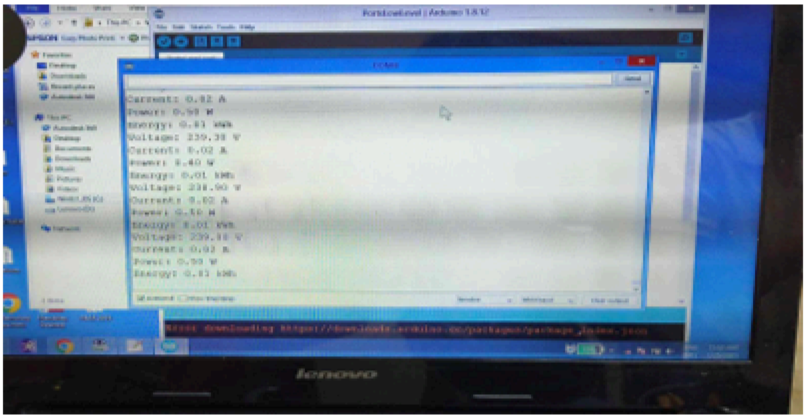


Figure 5
Serial Output verification through Arduino Serial Monitor



Load Testing and Accuracy Verification

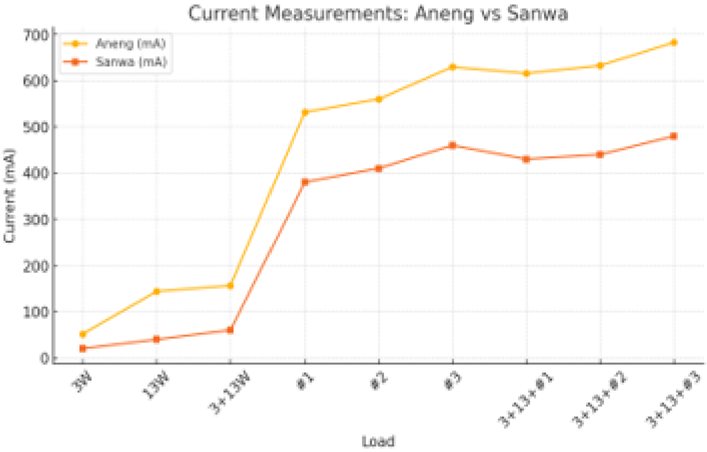
To ensure that the system accurately measured current, several test loads were used in conjunction with a verified clamp meter. These included low-wattage and moderate appliances. To assess current accuracy, two clamp meters were used: the SANWA (used as the reference due to its proven accuracy) and the Aneng clamp meter (a recent purchase for comparison).

Current measurements were conducted to three test devices:

- A 3-watt LED bulb
- A 13-watt LED bulb
- A 60-watt oscillating stand fan (tested at levels 1, 2, and 3)

Figure 6

Comparison of readings between SANWA and Aneng Clamp Meters



Based on clamp meter readings for various electrical loads, it was observed that the Aneng clamp meter consistently measured higher current than the Sanwa clamp meter. Given that the Sanwa meter was used as the basis for accuracy, the discrepancies indicate that the Aneng meter exhibited inaccuracies in current measurement.

For smaller loads, such as the 3W and 13W bulbs, the Aneng meter recorded significantly higher values than the Sanwa meter, with increasing deviations as the load increased. This trend continued for higher-power appliances, such as the fan, at different settings, further supporting the inconsistency in Aneng's readings.

Thus, it is concluded that the Aneng clamp meter may not be reliable for precise current measurements, and the Sanwa clamp meter should be preferred for more accurate readings in future experiments.

Table 1

Calibration of the Current Transformer

Load	Sanwa (mA)	PZEM (mA)
5W	20	30
3W	20	30
13W	40	64
5+3W	50	76
13+3W	60	85
13+5W	60	85
90W Fan	310	310
90W+Bulbs	320	310
Laptop	270	270
Laptop + Bulbs	320	310
Laptop + Fan + Bulbs	550	540

Table 1 presents the calibration results for the current transformer (CT) used in the Wattcher system, comparing current readings from the calibrated PZEM module with those from the reference clamp meter (Sanwa). A calibration factor of **0.85** was applied to the PZEM current measurements to align them with the Sanwa readings. As shown, after calibration, the PZEM values closely matched the reference measurements across a range of load conditions, from low-wattage bulbs (3W to 13W) to combined and higher loads such as laptops and fans. Notably, both the Sanwa and calibrated PZEM readings yielded nearly identical values at higher loads, such as the 90W fan and full system load (Laptop + Fan + Bulbs), demonstrating that the applied factor effectively improved the system's measurement accuracy, particularly under higher current draw.

Figure 7

Calibration of the Current Transformer

Enclosure and Mounting of System Components

To protect electronic components and ensure system longevity, a DIN rail-mounted screw terminal block adapter was used. This adapter not only provides secure, stable wiring connections but also offers modular expansion, making future upgrades or maintenance easier. Each wire was tightly clamped in place, reducing the risk of loose connections that could lead to signal loss or electrical faults. Furthermore, the PZEM-004T modules and Arduino controllers were enclosed in specially designed heat-resistant casings. These enclosures are essential for maintaining safe operating temperatures during continuous use and for efficiently dissipating generated heat. In addition to thermal protection, the casings also shield the internal components from environmental contaminants such as dust, which could otherwise interfere with sensor readings or damage sensitive electronics. Overall, these protective measures contributed to the reliability and durability of the Wattcher system, especially when deployed in real-world conditions where exposure to heat and debris is common.

Installation of Energy Monitoring Components

The installation process began with integrating PZEM-004T energy meters and current transformers (CTs) into the electrical panel of the TTBDO Building. Each CT was securely clamped around the designated phase wires to ensure accurate current measurement, while the PZEM modules were connected to the Arduino microcontrollers for data acquisition. The connections were configured with proper isolation and grounding to prevent electrical faults and ensure safety. The Arduino Ethernet Shield was integrated to allow wired data transmission, ensuring low latency and reliable communication between the monitoring system and the centralized PC for real-time data visualization.

Figure 8

Mounting of PZEM and other system components to the DIN rail

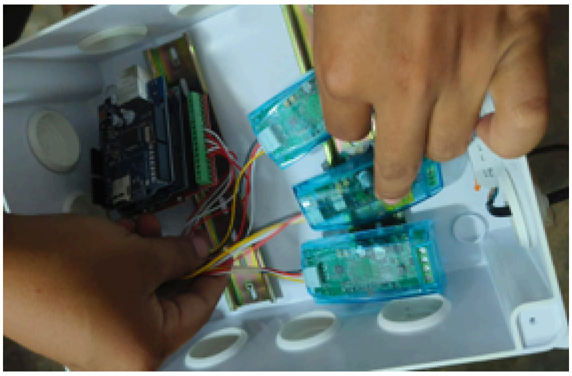
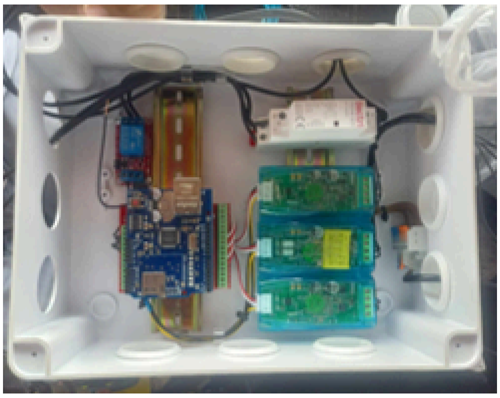


Figure 9

Hardware Connections of Wattcher

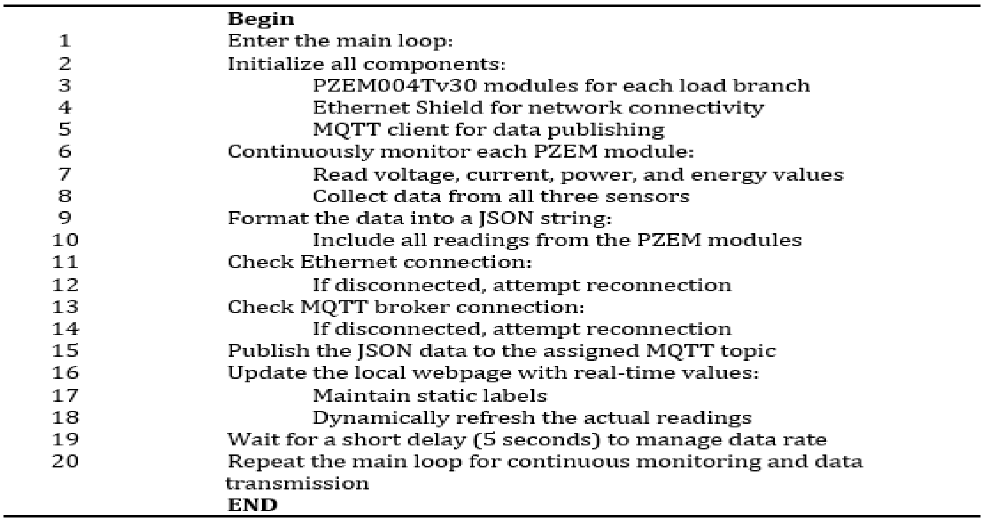


Software Design

The Wattcher system's software logic was structured to continuously collect, format, transmit, and display real-time energy monitoring data. Below is the summarized flow of the implementation:

Table 2

Wattcher Algorithm



```
Begin
Enter the main loop:
Initialize all components:
    PZEM004Tv30 modules for each load branch
    Ethernet Shield for network connectivity
    MQTT client for data publishing
Continuously monitor each PZEM module:
    Read voltage, current, power, and energy values
    Collect data from all three sensors
Format the data into a JSON string:
    Include all readings from the PZEM modules
Check Ethernet connection:
    If disconnected, attempt reconnection
Check MQTT broker connection:
    If disconnected, attempt reconnection
Publish the JSON data to the assigned MQTT topic
Update the local webpage with real-time values:
    Maintain static labels
    Dynamically refresh the actual readings
Wait for a short delay (5 seconds) to manage data rate
Repeat the main loop for continuous monitoring and data
transmission
END
```

Software Implementation

This section presents the software implementation of the Wattcher energy monitoring system. The software is responsible for acquiring data from the energy meters, transmitting the data via Ethernet, and displaying the values on a web-based interface. Development was done using the Arduino IDE with support from external libraries for the PZEM004T module and Ethernet shield.

Arduino Programming for PZEM004T

The Arduino Uno served as the central controller for data acquisition. It was programmed to interface with the PZEM-004T v3.0 energy monitoring modules, using the PZEM004Tv30 library to read real-time parameters, including voltage, current, power, and energy. Communication between the Arduino and the PZEM modules was established via software serial on digital pins.

F. Treatment of Data

A t-test was conducted to compare the current readings obtained from the current transformer (CT) sensors with those from a reference clamp meter. The results revealed a statistically significant difference between the two sets of readings ($p < 0.05$), indicating that the CT values differ from the clamp meter measurements.

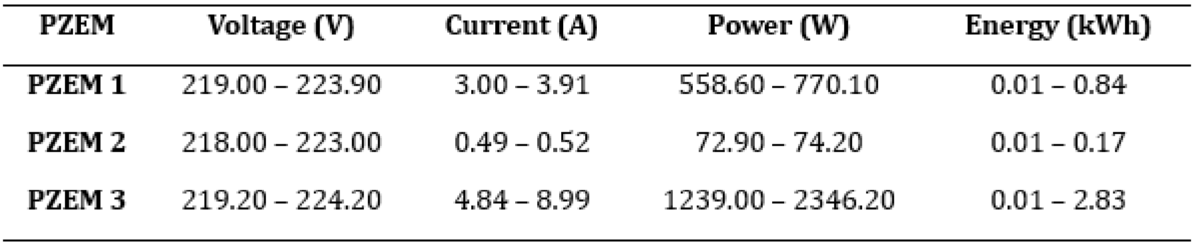
However, this statistical difference does not imply that the CT readings are inaccurate. Instead, the variation may be attributed to systematic bias or calibration offset, which is a common characteristic of low-cost or uncalibrated current sensors. The CT readings, while differing in absolute value, showed consistent behavior across repeated trials. This consistency supports the system's reliability in tracking changes in current over time.

Therefore, although the CT sensors may not match the clamp meter values exactly, they remain effective for monitoring trends, detecting operational patterns, and identifying anomalies in energy consumption. For future development, calibration procedures can be implemented to minimize this variance and improve measurement accuracy.

RESULTS AND DISCUSSION

Three circuit breakers (branches) were monitored in the TTBDO Building from 11:11 am to 12:11 pm on April 25, 2025. However, due to the lack of labeling in the panel board as regards the nature of the breakers - whether lighting or convenience outlet- the labels were not defined. The following are the documentation, summarized readings, and their interpretations.

Table 3
Summary of Observations

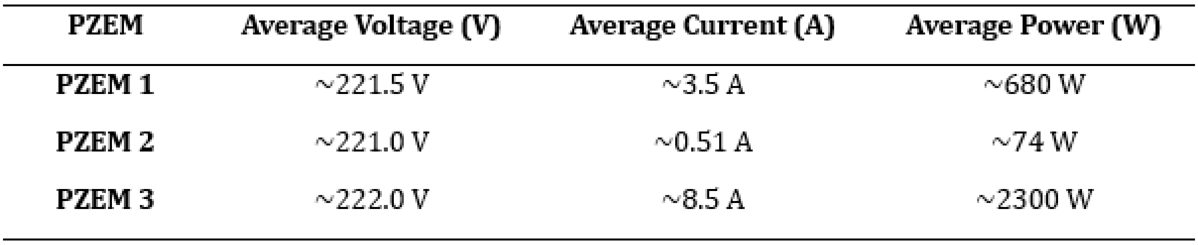


PZEM	Voltage (V)	Current (A)	Power (W)	Energy (kWh)
PZEM 1	219.00 – 223.90	3.00 – 3.91	558.60 – 770.10	0.01 – 0.84
PZEM 2	218.00 – 223.00	0.49 – 0.52	72.90 – 74.20	0.01 – 0.17
PZEM 3	219.20 – 224.20	4.84 – 8.99	1239.00 – 2346.20	0.01 – 2.83

Detailed Interpretation

- PZEM 1 (likely lighting or moderate load branch)
    - Voltage stayed relatively stable around 219–224V.
    - Current varied from 3.00 A to 3.91 A, indicating steady load.
    - Power ranged between 558.60 W and 770.10 W.
    - Slight dips around 3.00 A, but no sudden fluctuations suggest stable usage.
- PZEM 2 (light load branch, possibly for low-power devices)
    - Very stable, with current consistently around 0.49–0.52 A.
    - Power was steady at ~73–74 W.
    - No notable peaks or dips — indicates a continuously operating light load.
- PZEM 3 (high-power load branch)
    - This line shows the most dynamic behavior.
    - Current rose significantly from 4.84 A to 8.99 A.
    - Power rose dramatically from 1239.00 W up to 2346.20 W.
    - Likely powering heavier loads (e.g., air conditioning, motorized equipment).

Table 4
Averaged Readings

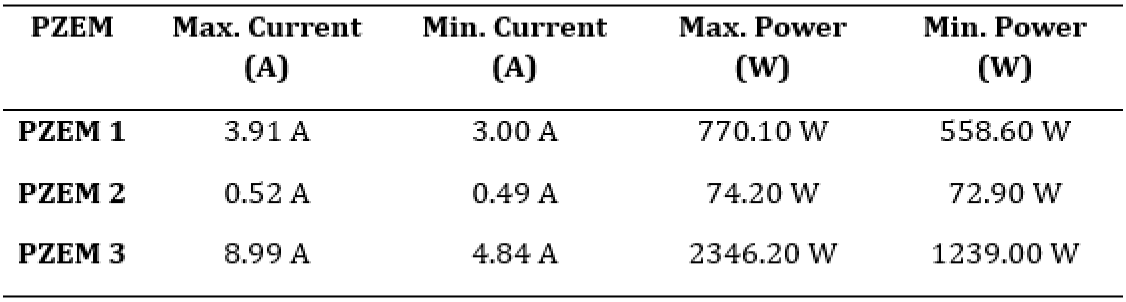


PZEM	Average Voltage (V)	Average Current (A)	Average Power (W)
PZEM 1	~221.5 V	~3.5 A	~680 W
PZEM 2	~221.0 V	~0.51 A	~74 W
PZEM 3	~222.0 V	~8.5 A	~2300 W

General Insights

- Voltage across all three branches remained steady and within normal distribution (~218–224V).
- PZEM 2 is very stable and low-load, suitable for small appliances or always-on devices.
- PZEM 3 represents significant consumption and shows peak loads, which could indicate large machinery, multiple devices turning on, or reactive loads.

Table 5
Maximum and Minimum Summary



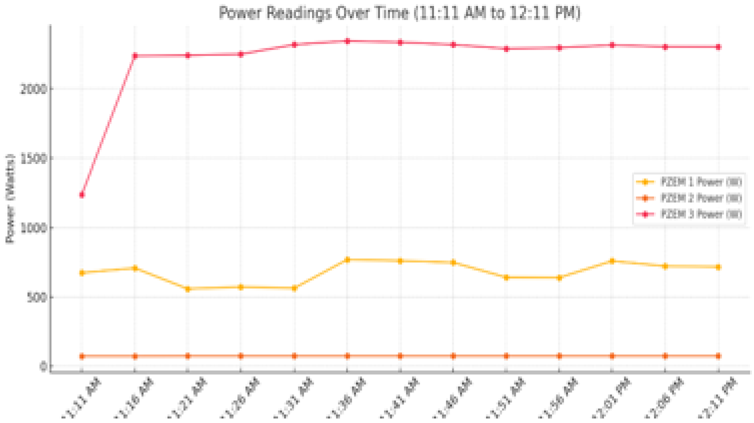
PZEM	Max. Current (A)	Min. Current (A)	Max. Power (W)	Min. Power (W)
PZEM 1	3.91 A	3.00 A	770.10 W	558.60 W
PZEM 2	0.52 A	0.49 A	74.20 W	72.90 W
PZEM 3	8.99 A	4.84 A	2346.20 W	1239.00 W

- The system is sensitive enough to capture subtle changes in load behavior.

Table 6
Readings Every 5 Minutes

Time	PZEM 1 Power (W)	PZEM 2 Power (W)	PZEM 3 Power (W)
11:11 AM	675	73	1239
11:16 AM	709	73	2238
11:21 AM	559	74	2242
11:26 AM	573	74	2250
11:31 AM	564	74	2319
11:36 AM	770	74	2346
11:41 AM	762	74	2336
11:46 AM	749	74	2319
11:51 AM	642	74	2290
11:56 AM	640	74	2297
12:01 PM	760	74	2316
12:06 PM	723	74	2304
12:11 PM	718	74	2303

Figure 10
Line Graph of Power Readings Over Time



Notes:

- Peak for PZEM 1 at 770 W recorded at 11:36 AM.
- Min. for PZEM 1 at 559 W recorded at 11:21 AM.
- Peak for PZEM 3 at 2346 W recorded at 11:36 AM.
- Min. for PZEM 3 at 1239 W recorded at 11:11 AM.
- PZEM 2 remained flat around 73–74 W throughout.

Summary Interpretation:

- PZEM 1 (Circuit 1) had relatively stable but modest power consumption, fluctuating between ~559 W to ~770 W.
    - Average Power ≈ 667.6 W
    - Peak Power = 770 W
    - Lowest Power = 559 W
- PZEM 2 (Circuit 2) showed very consistent low power readings (~73–74 W) throughout the recording.
    - Average Power ≈ 73.8 W
    - Peak Power = 74 W
    - Lowest Power = 73 W
- PZEM 3 (Circuit 3) indicated much higher and fairly stable heavy power usage.
    - Average Power ≈ 2263.8 W
    - Peak Power = 2346 W
    - Lowest Power = 1239 W (early point; otherwise stable)

Analysis Insights:

- PZEM 1's variation suggests moderate appliance loads switching on/off (like lights, small aircon units, or office equipment).
- PZEM 2's near-flat reading hints at a small continuous load, like emergency lighting, server equipment, or standby devices.
- PZEM 3's consistently high readings suggest a major appliance load — possibly large air conditioning systems, pumps, or clustered electronics. The early low reading could be before full system startup.
- No sudden drops or dangerous spikes were observed, suggesting stable operational behavior during monitoring.

Statistical Analysis Interpretation

A t-test was conducted to compare the current readings obtained from the current transformer (CT) sensors with those from a reference clamp meter. The results revealed a statistically significant difference between the two sets of readings ($p < 0.05$), indicating that the CT values differ from the clamp meter measurements.

However, this statistical difference does not imply that the CT readings are inaccurate. Instead, the variation may be attributed to systematic bias or calibration offset, which is a common characteristic of low-cost or uncalibrated current sensors. The CT readings, while differing in absolute value, showed consistent behavior across repeated trials. This consistency supports the system's reliability in tracking changes in current over time.

Therefore, although the CT sensors may not match the clamp meter values exactly, they remain effective for monitoring trends, detecting operational patterns, and identifying anomalies in energy consumption. For future development, calibration procedures can be implemented to minimize this variance and improve measurement accuracy.

Clamp Meter vs CT Sensor Accuracy

To assess the accuracy of the current transformer (CT) sensors relative to a standard clamp meter, two current readings from each instrument were recorded across three monitored circuits (PZEM 1, 2, and 3). A paired t-test was applied to determine whether there was a statistically significant difference between the clamp and CT readings.

To find out the values of the t-test, the following formula was used:

Table 7

Current Transformer vs Clamp Meter Readings in Amperes

Set	Clamp Meter	CT Sensor	Clamp Mean	CT Mean
1	2.67, 2.77	3.42, 3.56	2.72	3.49
2	0.33, 0.35	0.49, 0.49	0.34	0.49
3	5.55, 5.55	4.84, 4.83	5.55	4.84

$$t = \frac{m - \mu}{s/\sqrt{n}}$$

t = student's t-test

m = mean

μ = theoretical value

s = standard deviation

n = variable set size

T-Test Results:

- PZEM 1: p-value < 0.05 → Significant difference
- PZEM 2: p-value < 0.05 → Significant difference
- PZEM 3: p-value < 0.05 → Significant difference

The results indicate that in all three circuits, there is a statistically significant difference between the clamp meter and CT readings. This does not necessarily mean the data is inaccurate, but rather that the CT sensors consistently measure differently from the clamp meter, likely due to calibration differences or tolerances inherent in the CTs.

The energy monitoring and control system was successfully developed using CT sensors, PZEM modules, and Arduino microcontrollers, achieving real-time monitoring across three electrical branches. Despite slight variations between CT and clamp meter readings, the system demonstrated consistent performance suitable for tracking energy usage trends. The prototype, implemented in the TTBDO Building of Saint Mary's University, included centralized LAN-based monitoring and a simulated control feature through a contactor, laying the groundwork for future smart load management. Based on the findings, several improvements are recommended: calibrating CTs more rigorously to improve measurement accuracy, expanding monitoring coverage to include additional circuits, and incorporating advanced analytics and visualizations to provide richer insights. Developing a user-friendly web or mobile interface and safely integrating real-world control functions are also suggested to enhance usability and system functionality.

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