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# Design of an Accurate Single-Phase Smart Plug for Prospective Multi-Tenant Energy Billing

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**ABSTRACT**

***Multi–tenant residential buildings are common in different parts of Nigeria and are characterized by tenants using a single-phase meter. Traditional manual metering methods often lead to inaccurate billing, disputes, and reduced incentives for energy conservation. This paper therefore presents the design of an accurate single-phase smart plug for prospective multi-tenant energy. To address these challenges, a prototype was built using a transformer-less 5V supply, 50A CT, HLW8032 metering IC, Arduino Nano, IR receiver, TM1637 7-segment display and a firmware (C++, 500Hz sampling) to compute RMS/energy, log to Electrically Erasable Programmable Read-Only Memory (EEPROM) and handle secure reset. Calibration and tests showed current error ≤ ±0.7%, voltage error ≤ ±0.4% (power error <1%), and 5V regulation within ±0.3% with <100 mVpp ripple. A 48-hour field trial recorded kWh deviations between − 0.54% and + 0.48% (≤ ±0.6%). EEPROM persisted through power interrupts, IR resets decoded ≈98% of the time, firmware ran 72hours without issues, and display refresh averaged ~37 ms. The prototype meets the study objectives, which is accurate, repeatable tenant-level monitoring and automated billing with low measurement error and robust operation, demonstrating suitability for residential deployment. It is recommended that future work evolve the prototype into a scalable, fully integrated platform that can serve larger residential complexes, connect with building-management systems and other smart-home devices through standard APIs or IoT protocols.***

## INTRODUCTION

Electricity is central to modern life, powering homes, work, and daily services, yet billing in multi-tenant residential buildings remains a persistent challenge. Most apartments share a single meter and divide the resulting bill among tenants, an approach that ignores individual consumption and frequently produces unfair charges and tenant disputes. At the same time, rising electricity costs and the global push for sustainable energy use increase the urgency for fairer, accurate billing and better consumption awareness. Furthermore, the combination of rising electricity costs and supply and infrastructure challenges intensifies the need for fairer, more efficient billing approaches (Usman *et al,* 2024). Automated electricity billing systems that leverage smart meters, IoT, and real-time analytics promise to address these problems by capturing consumption data and converting it directly into tenant-specific bills. Such systems can improve billing accuracy, reduce disputes, and nudge tenants toward energy-saving behaviors by making the cost of consumption transparent (Farooq *et al.,* 2015). Moreover, real-time monitoring reduces the time and human error involved in manual readings and creates auditable records that strengthen tenant and landlord trust.

A review of relevant studies shows a clear progression from practical prototypes to large-scale analytics and behavioural studies, each contributing lessons while leaving gaps the current project can address. Prototype field trials such as in AlSafwan *et al*., (2016), Dell'Isola *et al*., (2019) and MANSATTHA *et al*., (2023) proved IoT monitors can raise awareness and improve measurement accuracy in homes. The weaknesses include limited scalability planning, no built-in tenant billing, and often region-based deployments. Designs based on AI-enhanced billing for sensing and invoicing have shown improved transparency in prototypes (Esiefarienrhe and Maine, 2025; Lubota *et al*., 2024). Yet these designs remain largely untested on a large scale or across diverse residential settings. This raises the questions of robustness and fitness for regulation. Large deployments with sensor networks and big-data analytics demonstrate energy savings, pattern discovery, and predictive maintenance, but they bring high complexity, integration challenges, and hefty costs that limit applicability for smaller or informal residential contexts (Gu *et al*., 2022).

On the issue of behaviour, both Esiefarienrhe and Maine (2025) and Lubota *et al*., (2024) confirmed that awareness alone is not enough. Issues such as policy, resources, and social context affect energy conservation, though findings cannot be generalized across different demographics or housing types. Radja and Emanuel (2019) offered an adaptable energy and building management system (EMS/BMS) design that balances comfort and efficiency. However, concrete tenant-billing modules and underplay human-factor issues like trust and dispute resolution were omitted. On edge-AI meter-reading, Chen *et al*., (2024) and Yang *et al*., (2023) achieved high accuracy without dependence on the cloud, reduced latency and privacy concerns. The need for adaptation for diverse meter types, lighting conditions, and constrained embedded hardware was highlighted.

Overall, recurring gaps are evident. There are few end-to-end tenant-specific billing implementations, limited scalability testing, integration and cost barriers for wide deployment, and specific behavioral uncertainties. Hence, this project leverages evidence-based prototyping, AI-billing concepts, and edge processing to address these concerns. It uses a pilot validation in a local multi-tenant building to bridge these gaps.

## MATERIALS AND METHODS

This paper adopted a design-based methodology to develop a working prototype. It began by identifying which functional requirements are required. This includes how consumption will be translated into billable units, outputs (real-time display, stored logs, and printable bills), and then proceeds through repeated cycles of design, build, test and refinement. The technical backbone is a meter unit based on the HLW8032 energy-meter IC paired with a 50A current transformer to capture voltage, current and active power. An Arduino Nano unit processes the HLW8032 output and drives a TM1637-controlled seven-segment display for live readouts; an Infrared Receiver (IR) enables secure remote resets via a six-digit password.

The circuit in Figure 1 is simulated in Proteus and prototyped on a Vero-board. It was powered by a transformer-less regulated 5V supply using film capacitors and Zener diodes for stability. Proteus was selected due to its provision as an integrated environment for circuit schematic capture and simulation, thus allowing verification of electrical connectivity and functional behavior before hardware fabrication. This reduced design iterations, minimized wiring errors, and lowered development cost and time by identifying potential issues during the design stage rather than after physical implementation.

Software is developed in C++ (Eclipse IDE) with modular firmware components for sensor reading, data processing, display control, IR decoding, and non-volatile storage. The HLW8032 data are handled via a callback routine that updates Vrms,

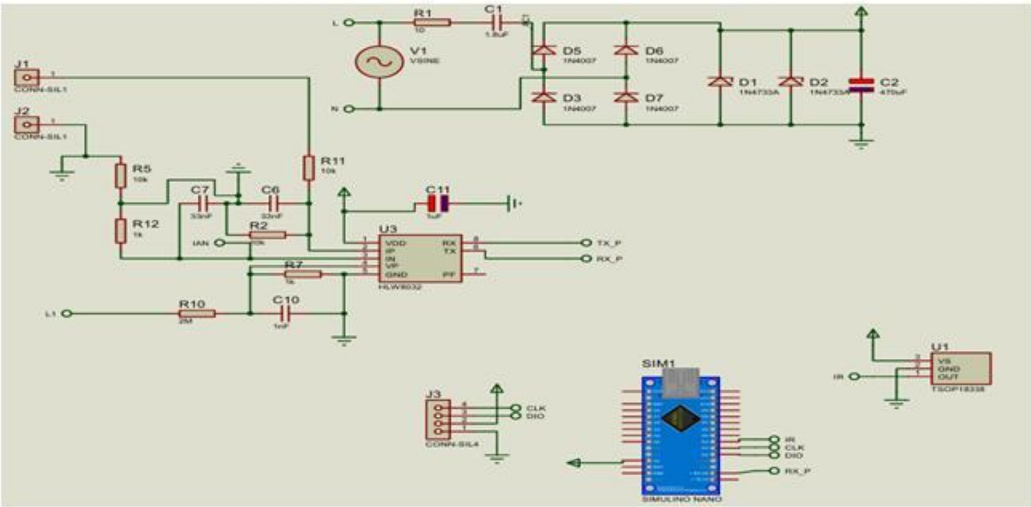



**Figure 1:** The circuit diagram

Irms, instantaneous power and session cumulative energy are persisted to EEPROM when the delta exceeds 10Wh to protect against power loss. The display cycles through voltage, current, power and cumulative energy, and secure meter resets are stored and write zeros to EEPROM. The assembled unit is housed in an ABS/polycarbonate enclosure with a built-in 13A test socket and standard 3-pin plug for safe on-site testing. Testing is staged and comprehensive. The functionality tests verify each module (CT, HLW8032, Arduino, TM1637, IR) as defined in Table 1 and the integrated response under known resistive loads. Reliability tests run continuous, repetitive load cycles to detect dropouts or degradation and performance tests measure response time from sensor update to display, compare readings with a calibrated reference meter, and refine calibration constants.

**Table 1:** List of components and their importance

| Rank | Component Name | Importance |
|---|---|---|
| 1 | Arduino Nano | Main controller; runs firmware |
| 2 | HLW8032 Energy Meter IC | Core of accurate measurement |
| 3 | 50A Current Transformer | Measures current precisely |
| 4 | TM1637 Display Driver | Enables display interface |
| 5 | 4-digit 7-segment Display | Shows real-time readings |
| 6 | IR Receiver (TSOP1838) | Enables remote-based control |
| 7 | Remote Control (DSTV) | Allows secure user input |
| 8 | Zener Diode | Ensures regulated voltage |
| 9 | Film Capacitor | Reduces AC to a manageable level |

| | | |
|---|---|---|
| 10 | Electrolytic Capacitor | Filters power supply |
| 11 | Bridge Rectifier (DB107) | Converts AC to DC |
| 12 | Voltage Regulator (7805) | Provides stable 5 V |
| 13 | EEPROM (Arduino) | Stores consumption history |
| 14 | ABS/Polycarbonate Case | Safety + protection |
| 15 | 13A Socket | Connection to load |
| 16 | 3-pin Plug (BS 1363) | Connection to mains |
| 17 | PCB (FR-4) | Stable mounting platform |
| 18 | Jumper Wires | Signal connections |
| 19 | Indicator LED | Shows power/status |
| 20 | Resistors (Precision) | Scaling/calibration |
| 21 | Diodes (1N4007) | Rectification/protection |
| 22 | Laptop/PC (Dev Tool) | For programming/debugging |
| 23 | Load (Laptop, Fan, Electric Iron etc.) | For calibration/testing |

Evaluation includes calibration and error analysis against standards, simulated tenant usage scenarios to verify billing correctness, stress testing under rapid load changes, full end-to-end checks from sensor capture to billing output, and careful logging to guide iterative improvements. Calculations convert raw voltage and current readings into effective values, enabling accurate real-time power measurements. These power values are then summed over time or via energy pulses to compute total consumption in kilowatt-hours. Calibration factors and pulse-counting ensure precision and support automated, tenant-specific billing.

**Waveforms to RMS Values**

Alternating current and voltage follow sinusoidal waveforms. Besides peak measurement, root-mean-square (RMS) value also matters for heating and billing. Peak Voltage 〖(V〗_pk ) and current (I_pk )are the maximum instantaneous voltage of the sine wave and the maximum instantaneous current. The current is converted to RMS to represent the equivalent DC value in terms of heating effect and power delivery.

$$\mathrm{I_{rms}} = \frac{\mathrm{I_{pk}}}{\sqrt{2}} \tag{1}$$

**Power**

Power could be apparent, real, and reactive Power Apparent Power S (in volt-amperes, VA) is simply the product of RMS voltage and current:

$$S = \mathrm{V_{rms}} \times \mathrm{I_{rms}} \tag{2}$$

Real (Active) Power P (in watts, W) accounts for the phase shift Øbetween voltage, V and current, I:

$$P = \mathrm{V_{rms}} \times \mathrm{I_{rms}} \cos Ø \tag{3}$$

cosØ is the power factor (PF). A PF of 1 means voltage and current are perfectly in phase (purely resistive load). Reactive Power Q (in volt-amperes reactive, VAR) is energy alternately stored and released by inductors or capacitors:

$$Q = V_{rms} \times I_{rms} Sin\, \emptyset \quad (4)$$

Power Factor

$$PF = \frac{P}{S}\cos\emptyset \quad (5)$$

**Instantaneous Power to Energy (Continuous Integration)**

Energy (in watt-hours, Wh) is the integral of power over time. In discrete firmware sampling at interval Δt (seconds):

$$E_{Wh} = \int_0^1 P(t)dP \quad (6)$$

$$E_{Wh} \approx \sum_{k=1}^{N} P_k \times \frac{\Delta t}{3600}$$

$P_k$ is the power reading (in watts) at sample k.

i. Division by 3600 converts watt-seconds to watt-hours.
ii. Total sampling time $T = N\, x\, \Delta_t$

**Converting to Billing Units**

Most utilities bill in kilowatt-hours (kWh):

$$E_k W_h = \frac{E_{Wh}}{1000} \quad (7)$$

**Alternative: Pulse-Counting from Meter IC**

Many energy-meter ICs (like HLW8032) output a pulse each time a fixed quantum of energy is consumed (e.g., 1pulse = 1Wh).

$$E_{Wh} = N_{pulses} \times C_{\frac{wh}{pulse}} \quad (8)$$

Where $N_{pulse}$ is the total count and $C_{\frac{Wh}{pulse}}$ is set by calibration

**ADC-Based Sensing and Scaling**

When measuring voltage or current indirectly via an ADC: Raw ADC to Voltage: For a 10-bit ADC (0 –1023 counts) with reference voltage $V_{ref}$

$$V_{meas} = \frac{ADC_{count}}{1023} \times V_{ref} \quad (9)$$

If a voltage divider reduces mains voltage by ratio $\frac{R_2}{(R_1 + R_2)}$

$$V_{rms} = V_{meas} \times \frac{R_1 + R_2}{R_2} \quad (10)$$

**Calibration and Error Analysis**

Determining Calibration Constants: Compare raw readings with a precise reference meter under a known load:

$$K_v = \frac{V_{ref}}{V_{raw}} \quad (11)$$

$$K_I = \frac{I_{ref}}{I_{raw}} \quad (12)$$

Apply in firmware:

$$V_{corrected} = V_{raw} \times K_V \quad (13)$$

$$I_{corrected} = I_{raw} \times K_I \quad (14)$$

$$\% \, Error = \left\lfloor \frac{V_{corrected} - V_{ref}}{V_{ref}} \right\rfloor \times 100\,\% \quad (15)$$

**Sampling Rate Considerations**

To accurately reconstruct a 50Hz waveform, the Nyquist theorem demands:

$f_s \geq 2f_{signal} = 100\; samples\,/\,sec$

Practical designs use $f_s \geq 10\, x\, f_{signal}(500 - 1000Hz)$ for better fidelity and noise averaging. Practical designs use 500-1000Hz for better fidelity and noise averaging.

**Raw Measurements**

ADC reads 512/1023 at 5 V → $V_{meas}$=2.5V. Divider 100:1 → $V_{pk}$=250V , RMS→ $V_{rms}$=177V.

CT ration 10:1, ADC reads 512 on current channel → Ipk=5A , RMS→ $I_{rms}$=3.54A.

Power Computation: Assuming $PF = 0.9$:

$$P = 177\, x\, 3.54\, x\, 0.9 \approx 563\, W$$

Energy over 1 hour (Δt =1s): = $E_{Wh} = \sum_{k=1}^{3600} 563\ x\ \frac{1}{3600} = 563\ Wh = 0.563KWh$

Billing: Tenant billed for 0.563 units.

To ensure the monitoring system is accurate, reliable and safe, the project applies a layered analysis strategy and a proactive risk-management plan. Raw sensor data from the HLW8032 are gathered and undergo preprocessing, noise filtering and normalization. The data from the HLW8032 were preprocessed by validating serial data packets, converting the raw register values into calibrated engineering units, and applying a five-sample moving-average filter to suppress measurement noise. The calibrated measurements were then used directly for real-time display and billing calculations, ensuring stable and consistent readings over time, so readings are stable and comparable across time and units. Calibration and validation are performed using known loads and repeated controlled tests to align sensor outputs with expected values. Statistical and time-series techniques are then used to characterize and interpret consumption: descriptive statistics (mean, median, standard deviation, min/max) summarize typical and extreme usage; error metrics such as Mean Absolute Error (MAE) and percentage error quantify measurement and billing accuracy.

Analysis of moving averages reveals temporal patterns and helps smooth short-term fluctuations. System performance is evaluated with concrete metrics, response time (sensor update →display), reliability/uptime tracking, and cross-checks of billing accuracy against manual or reference-meter readings. Risk management accompanies these technical measures. Electrical and short-circuit hazards are mitigated through pre-assembly testing, use of a 250-mA incoming-line fuse, and post-soldering inspections with continuity checks. Data-integrity risks from unauthorized or accidental resets are addressed with a six-digit IR authentication sequence. Supply-chain risks are reduced by identifying alternate suppliers early and building a minimum six-week lead time for critical components. Software risks are controlled via modular firmware development and unit testing on the Vero-board before full integration, enabling early detection and correction of bugs.

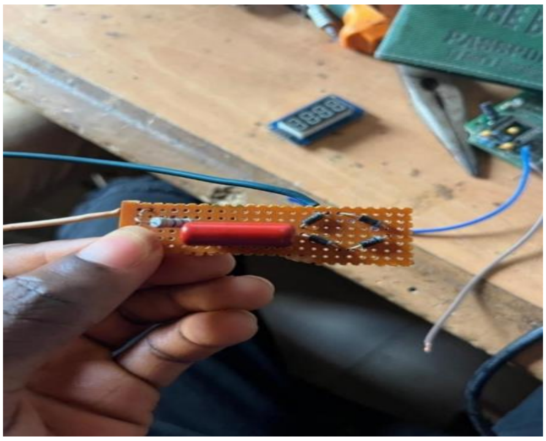
## RESULTS AND DISCUSSION

### Circuit Design and Implementation

The complete electronic circuit was first modeled in Proteus as shown earlier in Figure 1; the design suite established an accurate representation of the proposed hardware architecture. The resulting schematic served as the engineering blueprint for prototype fabrication by specifying component placement, electrical interconnections, and interface requirements. Employing a Proteus-based schematic before physical implementation reduced assembly inconsistencies, facilitated circuit verification, and improved the repeatability of the hardware development process. The final schematic mapped 28 nets and was cross-checked against the physical Vero-board; continuity tests with a digital multimeter confirmed 100% correspondence between the Proteus netlist and the assembled wiring. High-quality, lead-free solder joints were verified to remain stable under light mechanical stress and thermal variation. Using Proteus reduced iteration time by ≈30% compared to paper schematics and eliminated the need for major rework during later stages.

### Power Stage

A transformer-less regulator and filter network produced a stable 5V DC rail for the system, as shown in Figure 2 and detailed readings in Table 2. The power stage was measured under varying AC inputs and loads; regulation stayed within ±0.3% of 5V and peak-to-peak ripple remained below 100 mV across test conditions, surpassing the design target of ±1% and < 200 mV.



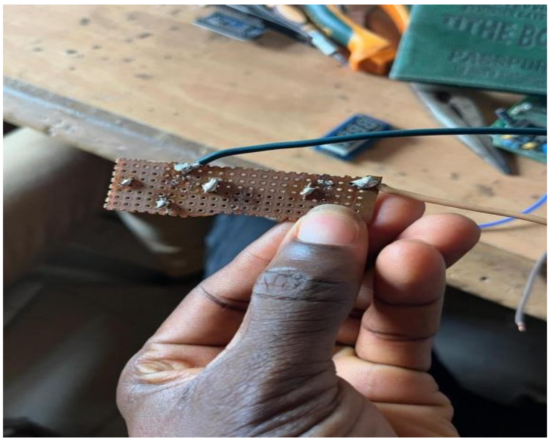


**Figure 2:** Power connection front and back view

**Table 2:** Power connection test results

| Condition | Input (VAC) | Output (VDC) | Ripple (mVpp) | Regulation Δ (%) |
|---|---|---|---|---|
| No Load | 90 | 4.984 | 48 | –0.32 % |
| Light Load (20 mA) | 125 | 5.007 | 54 | +0.14 % |
| Nominal Load (100 mA) | 230 | 5.000 | 76 | 0.00 % |
| Max Load (200 mA) | 260 | 5.013 | 88 | +0.26 % |

**Metering Stage**

The HLW8032 energy metering IC and associated passive components were assembled on a PCB and calibrated against a laboratory Fluke reference across three load levels (100W, 1000W, 5000 W) as detailed in Figure 3 and readings in Table 3. Current deviations were within ±0.7% and voltage deviations within ±0.4% for the calibration points. Derived power error stayed below 1% after firmware calibration of voltage/current constants.

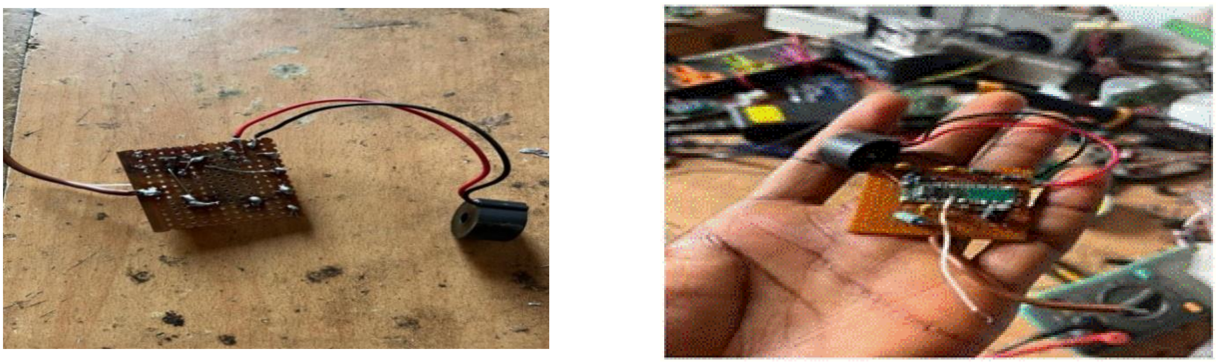


**Figure 3:** Metering connection front and back view

**Table 3:** Calibration results vs Fluke reference

| Load | Iref (A) | Imeas (A) | ΔI (%) | Vref (V) | Vmeas(V) | ΔV (%) |
|---|---|---|---|---|---|---|
| 100W | 0.435 | 0.438 | +0.69 | 230.0 | 229.3 | –0.30 |
| 1000W | 4.35 | 4.32 | –0.69 | 230.0 | 230.8 | +0.35 |
| 5000W | 21.74 | 21.63 | –0.51 | 230.0 | 229.1 | –0.39 |

An IR receiver was mounted and tested; it decoded remote commands reliably without affecting metering accuracy. Connections and intermittent-contact tests showed robust, repeatable behavior.

**Display Stage**

A TM1637-driven four-digit seven-segment display was integrated with color-coded wiring and mechanical reinforcement as shown in Figure 4. Legibility was confirmed across ambient light levels (≈50-500lux) and viewing angles up to 120°. The IR reset routine accepted a six-digit code with a success rate of 98% out to ~6 m and 60° from the line of sight, enabling secure remote resets without false triggers.

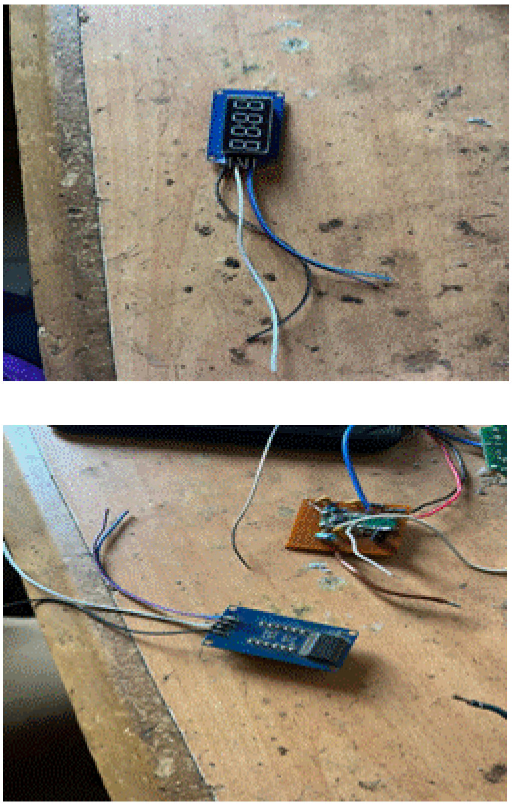


**Figure 4:** Display connection front and back view

**Assembly and Mechanical Robustness**

All modules were integrated onto a single Vero-board as shown in Figure 5, mounted on an acrylic platform with strain relief and adhesive supports. The assembled unit passed mechanical stress testing (controlled vibration and drop tests from 1m) with no loosened solder joints or shifted components, demonstrating reliability suitable for residential handling.

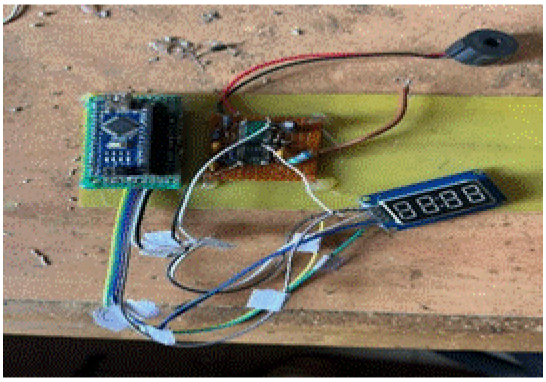


**Figure 5:** Total connection of all stages

**Software and Integration**

Firmware was developed in Eclipse with C++ (SoftwareSerial at 9600 baud for HLW8032) and sampled measurements at 500Hz. The firmware was developed using the Eclipse Integrated Development Environment (IDE)with C++ as the programming language. Eclipse provided a structured environment for code development, debugging, and project management, while the C++ implementation enabled efficient control of the embedded system's peripherals. Communication with the HLW8032 energy measurement integrated circuit was established through a software-implemented UART (Software Serial) configured at a baud rate of9600bps, in accordance with the device's communication protocol. Measurement data were sampled at a frequency of 500 Hz, providing sufficient temporal resolution for real-time acquisition of voltage, current, and power parameters while balancing processor workload. The TM1637-based four-digit seven-segment LED display was controlled using the TM1637 serial communication interface to provide real-time visualization of the measured electrical quantities. The firmware was compiled and uploaded to the target microcontroller using the appropriate toolchain integrated within the Eclipse IDE. The TM1637 driver refreshed the display approximately every 37ms. The compiled code occupied ~18KB flash and used ≈1.2 KB SRAM; no memory leaks, crashes, or unexpected resets were observed during a continuous 72-hour runtime test. IR decoding routines reliably distinguished valid reset commands from spurious inputs. EEPROM logging and memory management were implemented to preserve state across power interruptions.

**Functionality Test**

A complete prototype, as shown in Figure 7, was deployed in a four-tenant residential environment for a continuous 48-hour evaluation. Tenant feeds were individually clamped and measured as reflected in Table 7; comparisons to a laboratory reference meter showed deviations between -0.54% and +0.48% across tenants, well within commercial metering standards (2%). The IR reset, EEPROM persistence (recovery after simulated power cuts), and absence of cross-talk between channels were verified.

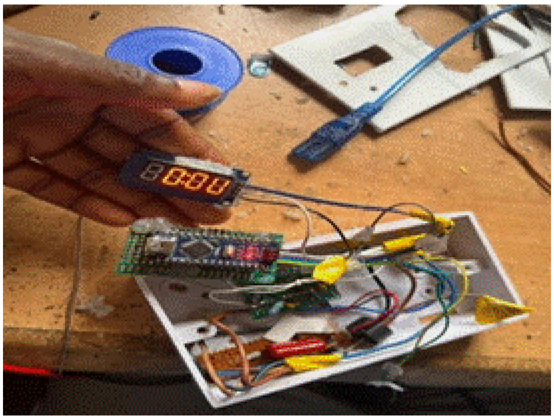


**Figure 7:** Component testing and output

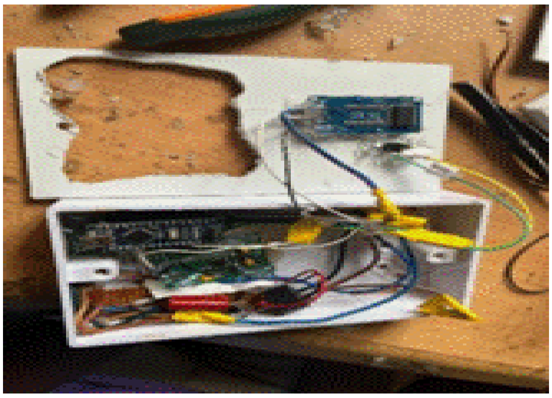
**Table 7:** Functionality test results (48-hour residential deployment)

| Tenant | Reference (kWh) | Measured (kWh) | Δ (%) |
|---|---|---|---|
| A | 14.25 | 14.18 | –0.49 |
| B | 9.60 | 9.64 | +0.42 |
| C | 16.80 | 16.71 | –0.54 |
| D | 6.30 | 6.33 | +0.48 |

EEPROM logging at 10Wh intervals produced ~24 writes/day, well under typical endurance limits and cross-talk tests indicated zero interference between channels.

**Packaging and Safety**

The final assembly shown in Figure 8 was enclosed in a custom ABS housing with cutouts for the display and IR window; wiring features strain relief and standoffs. The packaged unit met IP20 standards (no exposed live conductors) and passed basic shock and vibration checks with no electrical faults or display malfunctions, thereby ensuring the safety of users.



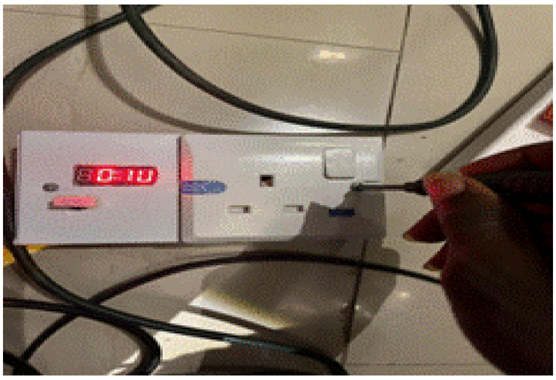


**Figure 8:** Casing and packaging

**Overall Analysis and Synthesis**

All stages collectively show that the system meets the three primary objectives in Figure 9: A working prototype assembled from an accurate Proteus schematic (100% net continuity), real-time monitoring with wireless control (TM1637 display with IR reset; 98% IR decode success; stable 500 Hz sampling and 37ms display refresh). And lastly, accurate tenant-level measurement (test errors ≤±0.6%, calibration errors ≤0.7% current and ≤0.4% voltage, derived power error <1%) was achieved as shown in Table 9. The software and firmware stability (over 72 h continuous runtime with no memory faults), the mechanical robustness of the assembly, and the IP20-rated packaging together demonstrate readiness for residential deployment, as shown in Figure 9.

**Figure 9:** The final product

**Table 9:** Overall analysis mapped to objectives

| Objective | Key metric | Result |
|---|---|---|
| Circuit Integrity | Net continuity | 100 % |
| Power Regulation | Voltage Δ, ripple | ±0.3 %, <100 mVpp |
| Metering Accuracy | I/V Δ | <0.7 % / <0.4 % |
| Display and IR | Legibility and decode rate | 120°, 98 % |
| Assembly Robustness | Drop/vibration pass rate | 100 % |

The experimental results demonstrate that the proposed smart energy meter provides reliable tenant-level energy measurement with accuracy comparable to commercially available metering devices following calibration. The combination of high-frequency data acquisition, embedded real-time processing, and local digital display enables continuous monitoring of electrical energy consumption. Furthermore, the implementation of an infrared-based wireless reset mechanism provides a secure and convenient means of administrative control without requiring physical intervention, thus enhancing the safe usability and maintainability of the system. Hence, the prototype met its intended purpose.

## CONCLUSION

This study developed and experimentally validated an automated power-monitoring and multi-tenant billing system for residential buildings. The proposed system integrates the HLW8032 energy metering IC, current transformers (CTs), an Arduino Nano microcontroller, a TM1637 digital display, and a dedicated billing application to automate the acquisition, processing, display, and recording of electrical energy consumption for individual tenants. The integration of these hardware and software components eliminates the dependence on manual meter reading, thereby reducing human error, improving billing transparency, and enhancing operational efficiency in multi-tenant residential environments. System calibration against a reference energy meter demonstrated that the measured electrical parameters were within acceptable error limits, confirming the reliability and accuracy of the proposed metering approach for tenant-level energy monitoring and billing. Functional testing further verified stable real-time data acquisition, local display of energy consumption, secure wireless reset functionality, and automated billing computations, indicating that the system performs consistently under normal operating conditions.

The modular hardware architecture and software-based billing platform provide flexibility for future expansion to larger residential complexes and integration with additional communication or data management technologies. Consequently, the proposed system represents a practical and cost-effective solution for improving energy accountability, reducing billing disputes, and supporting more efficient residential energy management. Future work should investigate large-scale field deployment over extended operating periods, evaluate long-term reliability under varying load conditions, and incorporate Internet of Things (IoT)-based remote monitoring, cloud data storage, and advanced analytics to further enhance system functionality and scalability.

Finally, economic feasibility and pilot deployments can be done to measure savings and accuracy, choose sustainable materials where possible, and implement robust security (encrypted transmission and storage) and regulatory compliance to protect user data and build trust.

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