

Design and Experimental Validation of a Low-Cost, IoT-Enabled Smart Power Meter for Low-Voltage DC Systems

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ABSTRACT: This paper presents the design and experimental validation of a low-cost Internet of Things-enabled smart power meter for low-voltage direct-current applications. The prototype integrates an ESP32 microcontroller, INA219 high-side current and voltage sensor, SSD1306 OLED display, Wi-Fi connectivity, and Blynk cloud telemetry. The system was evaluated using a 9 V battery source and different LED load configurations. Under the baseline test condition, the prototype measured a bus voltage of 8.94 V, load current of 15.10 mA, and power consumption of 0.13 W. During a 60-second discharge test, the measured voltage decreased from 8.94 to 8.80 V, while current decreased from 15.10 to 14.40 mA. Comparative LED testing produced current values between 14.80 and 16.50 mA, demonstrating the ability to distinguish small load-current variations. Local OLED readings were also transmitted to the Blynk dashboard at nominal one-second intervals. The proposed meter provides an inexpensive and replicable platform for educational laboratories, low-power DC energy auditing, and preliminary monitoring of decentralized renewable-energy systems.

KEYWORDS: Internet of Things (IoT); ESP32; INA219; Low-Voltage DC System; Blynk Cloud; Energy Monitoring.

I. INTRODUCTION

A. Background and Context

The global energy sector is undergoing rapid transformation driven by digitalization, sustainability imperatives, and the integration of smart-grid technologies [1]. Within this transition, intelligent metering systems have become central to improving operational efficiency, revenue assurance, and consumer trust in electricity networks. In Nigeria, however, persistent challenges such as energy pilferage, inadequate metering coverage, and inefficient revenue collection continue to undermine service quality and sector performance [2]. Despite policy interventions such as the Meter Asset Provider (MAP) scheme and the National Mass Metering Program (NMMP), a large proportion of consumers remain unmetered, eroding confidence and constraining system development [3].

The emergence of the Internet of Things (IoT) in energy systems has created new opportunities for real-time monitoring, control, and data-driven decision-making [5]. IoT-enabled meters can transmit telemetry to cloud platforms, enabling utilities and prosumers to analyze usage patterns, detect anomalies, and optimize distribution and consumption. In Nigeria and similar contexts, IoT-based solutions have been deployed to enhance accountability and efficiency in electricity, water, and gas services [6]. At the same time, the growing adoption of renewable energy technologies particularly solar photovoltaic (PV) systems and battery storage is shifting attention toward direct current (DC) microgrids and low-voltage DC networks [7]. Accurate DC

metering is essential for quantifying generation, storage, and load profiles in such systems and for supporting smart-grid integration. Cloud computing further complements these developments by providing scalable infrastructure for data storage, analytics, and remote access, thereby enabling real-time monitoring, predictive maintenance, and improved billing transparency [8, 9].

B. Problem Statement

Notwithstanding these technological advances, the Nigerian electricity sector continues to face significant operational deficiencies. A substantial share of consumers remains unmetered, resulting in estimated billing, revenue leakages, and consumer dissatisfaction [10]. Moreover, most existing metering solutions are designed for alternating current (AC) utility grids and do not address the specific requirements of low-voltage DC systems associated with solar PV, battery banks, and DC microgrids [7]. Many low-cost DC prototypes rely on the native analog-to-digital converters (ADCs) of microcontrollers, which often exhibit limited resolution, non-linearity, and susceptibility to noise [14]. In addition, current metering units frequently lack integrated IoT and cloud capabilities, limiting their usefulness for remote monitoring, data logging, and smart-grid applications [11]. These gaps impede the transition to intelligent, data-driven energy management in Nigeria and hinder progress toward Sustainable Development Goal 7 (Affordable and Clean Energy) [3].

C. Related Work and Research Gap

Existing literature on smart metering provides valuable insights but leaves important engineering and methodological gaps, particularly for low-voltage DC applications. First, most published studies focus on AC sensor design and prepaid or theft-detection schemes for utility grids, with limited attention to high-side DC shunt measurement and low-voltage DC microgrid assessment [2, 12, 13]. Second, many low-cost DC prototypes depend on the microcontroller’s internal ADC, which often yields coarse resolution and introduces non-linearity and noise into the measurement chain [14]. Third, designs that combine local visualization (e.g., OLED or LCD displays) with synchronized, low-latency cloud telemetry are uncommon in the low-cost segment; where cloud dashboards are implemented, update intervals are often several seconds or updates interfere with microcontroller execution threads [8, 15].

Collectively, these limitations indicate a need for an inexpensive, high-resolution DC metering solution that integrates robust sensing, local display, and reliable cloud telemetry without imposing significant hardware or computational overhead. Such a system would support educational laboratories, decentralized DC microgrid diagnostics, and localized energy auditing in resource-constrained settings.

D. Objectives and Contributions

To address these gaps, this study designs, implements, and experimentally validates an ultra-low-cost, IoT-enabled DC smart power meter based on an INA219 high-side current and voltage sensor and an ESP32 microcontroller. The work details the hardware architecture, firmware design, and empirical performance under representative low-voltage DC load conditions.

The main contributions of this paper are as follows:

1. Integration of an INA219 sensor module with an internal 12-bit ADC and a $0.1\ \Omega$ shunt resistor for DC bus voltage and current measurement up to 26 V and $\pm 3.2\text{ A}$, overcoming the resolution and linearity limitations of generic microcontroller ADCs [14].
2. Implementation of a non-blocking firmware architecture that simultaneously drives a local SSD1306 OLED display and transmits telemetry to the Blynk IoT cloud platform at nominal one-second intervals over Wi-Fi [9, 16].
3. Experimental evaluation using a 9 V battery source and multiple semiconductor LED loads, including dynamic discharge profiling and comparative load characterization across different optical wavelengths [5].
4. Provision of a fully replicable, open-hardware prototype with a bill-of-materials cost of approximately ₦20,000 (< \$15), suitable for educational laboratories, preliminary DC microgrid assessments, and localized energy audits [8, 9].

II. MATERIALS AND METHODS

A. System Architecture

The low-cost IoT DC smart power meter comprises three functional blocks: the Measurement Block, the Processing Block, and the Telemetry & Display Block. The Measurement Block acquires voltage and current data from the DC load using a high-side sensing module. The Processing Block digitizes, processes, and computes electrical parameters. The Telemetry & Display Block provides local visualization on an OLED screen and transmits data to a cloud dashboard over Wi-Fi. The overall architecture is illustrated in Fig. 1.

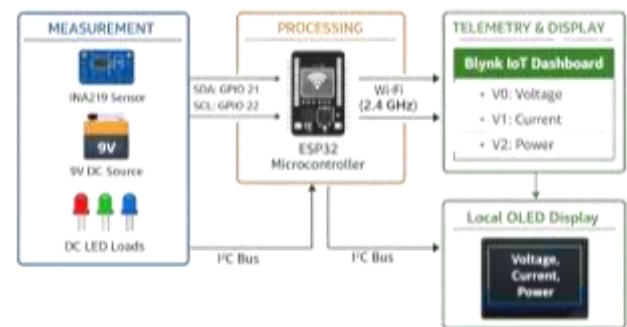


Fig. 1 System block diagram of the IoT DC smart power meter architecture.

This modular structure supports independent testing and replacement of each block, simplifies troubleshooting, and enables future upgrades (e.g., alternative sensors or communication protocols) without redesigning the entire system.

B. Hardware Components

The prototype integrates four principal hardware components:

1. **Microcontroller Unit:** The ESP32 was selected as the main processing engine and wireless gateway due to its dual-core 32-bit Tensilica LX6 architecture operating at 240 MHz, low operational power consumption, and integrated 2.4 GHz Wi-Fi connectivity [16, 27].
2. **High-Side DC Sensing Module:** The INA219 was chosen as an integrated high-side current and voltage monitoring IC communicating over a 100 kHz I²C bus. The module incorporates an internal 12-bit analog-to-digital converter (ADC) and an onboard $0.1\ \Omega$ shunt resistor, enabling measurement of DC bus voltages up to 26 V and bidirectional currents up to 3.2A with fine resolution, thereby overcoming the non-linearity and noise limitations of generic microcontroller ADCs [14].
3. **Local Display:** A 0.96-inch SSD1306 organic light-emitting diode (OLED) display was selected for local visualization. The monochrome screen is driven via the I²C protocol and provides instantaneous visibility of voltage, current, and power at the device enclosure.

4. DC Power Source and Semiconductor Loads: A 9 V heavy-duty battery pack served as the DC source. Light-emitting diodes (LEDs) of different semiconductor wavelengths (red, green, blue, white) were used as loads to evaluate the system’s sensing resolution under different forward current conditions [5].

Component costs were obtained from retail electronics markets in Nigeria. The total hardware cost of the prototype is approximately ₦20,000 (~\$14.60 at an exchange rate of ₦1,365/USD), excluding enclosure and labor. This is substantially lower than many commercial alternatives (> \$50). The itemized bill of materials is presented in Table I.

Table I Itemized Component Cost Breakdown for the Smart Meter Prototype.

Compon ent Descript ion	Model / Specificat ion	Qty	Unit Cost (NG N)	Total Cost (NG N)	Est. Cost (USD)*
Microco ntroller Unit	ESP32 NodeMCU Wi-Fi Board	1	₦8,500	₦8,500	~\$6.20
High-Side Sensing Module	INA219 I ² C Module (0.1 Ω Shunt)	1	₦4,500	₦4,500	~\$3.30
Local OLED Display	SSD1306 0.96" Screen (I ² C)	1	₦3,500	₦3,500	~\$2.55
Prototy ping Accessor ies	Breadboard, Jumpers, 9V Snap	1 set	₦3,500	₦3,500	~\$2.55
Total Hardwa re Cost	—	—	₦20,000	₦20,000	~\$14.60

*Note: Conversion calculated at the exchange rate of ₦1,365/USD. Excludes external enclosure and labor costs.

C. Circuit Interconnection and Sensing Principle

High-side current sensing was adopted to monitor electrical parameters while maintaining a common ground reference for the load and microcontroller. The wiring arrangement is shown in Fig. 2.

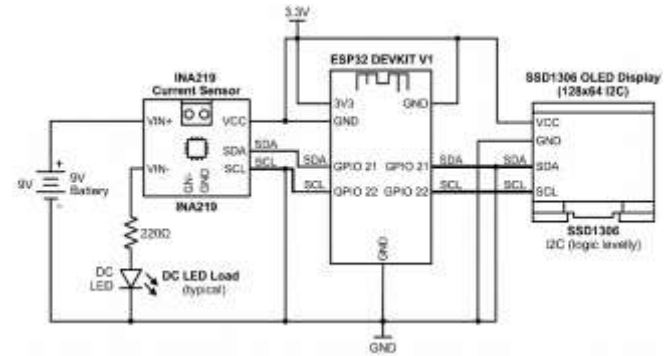


Fig. 2 Circuit schematic and interconnections of the IoT DC smart power meter.

The positive terminal (+) of the 9 V battery was connected to the VIN+ terminal of the INA219 module. The VIN– terminal was connected to the positive anode of the DC LED load. The load cathode was returned to a common ground shared by the battery negative terminal and the ESP32. The VCC pins of the INA219 sensor, and SSD1306 OLED display were powered from the 3.3 V output rail of the ESP32. All GND terminals were tied to a single common ground. The Serial Data (SDA) pin of the SSD1306 was connected to ESP32 GPIO 21, and the Serial Clock (SCL) pin to ESP32 GPIO 22, forming the I²C interface.

The INA219 measures the small differential voltage drop V_{shunt} across its internal 0.1 Ωshunt resistor. Load current I is derived internally via Ohm’s law:

$$I = \frac{V_{shunt}}{R_{shunt}}$$

Power consumption P is computed in the firmware as the product of bus voltage and measures current:

$$P = V_{bus}I$$

This approach eliminates the need for external amplification or complex analog signal-conditioning circuitry.

D. Firmware and IoT Telemetry Design

The control software was developed in C++ using the Arduino IDE. To avoid hardware blocking and display refresh delays, the firmware employs a non-blocking asynchronous timer loop instead of standard blocking delay() functions. [8]

On power-up, the ESP32 initializes the I²C bus at 100 kHz, verifies INA219 register readiness, configures the SSD1306 OLED display, and establishes a Wi-Fi connection to the Blynk cloud server. The main execution loop runs every 1,000 ms and performs the following operations: [9]

1. Polling the INA219 registers for bus voltage V_{bus} , shunt voltage V_{shunt} , and current I .
2. Computing power consumption P in watts.
3. Updating the local SSD1306 OLED display with the latest voltage, current, and power values.

4. Transmitting the measured parameters to the Blynk cloud platform over Wi-Fi using virtual pins V0 (bus voltage), V1 (load current), and V2 (calculated power) for remote dashboard visualization. [9]

This design ensures concurrent local display updates and cloud telemetry without freezing the microcontroller’s execution threads.

E. Experimental Setup and Procedure

The prototype was evaluated in a controlled laboratory environment at the Physics Laboratory, Federal Polytechnic Oko, Nigeria. A 9 V heavy-duty battery served as the DC source, and four LED loads (red, green, blue, white) with different semiconductor bandgaps were used to represent distinct electrical load profiles.

The experimental procedure comprised three phases:

1. Baseline Measurement Validation: A single red LED load was connected, and steadystate voltage, current, and power readings were recorded from both the OLED display and the Blynk dashboard.
2. Dynamic Battery-Discharge Analysis: Time-series data were collected at 10-second intervals over a 60-second period under a constant LED load to assess measurement stability and the system’s ability to track gradual changes in battery voltage and current.
3. Comparative LED Load Profiling: Each LED color was connected in turn, and corresponding voltage, current, and power values were recorded to evaluate the sensor’s resolution across different load currents.

All readings were logged manually from the OLED display and crosschecked against the Blynk cloud dashboard. Wi-Fi connectivity was maintained throughout the tests, with the access point located within typical indoor range of the prototype.

F. Evaluation Metrics

The performance of the prototype was assessed using the following metrics:

1. Steady-State Accuracy: Comparison of measured voltage, current, and power against expected ranges for a 9 V battery driving a standard 5 mm LED load.
2. Dynamic Tracking Capability: Observation of voltage and current trends over time to verify that the system could resolve gradual battery discharge without measurement jitter.
3. Load Resolution: Ability to distinguish small differences in current consumption among LED loads of different wavelengths.
4. Telemetry Consistency: Visual comparison of parameter values displayed on the local OLED screen and the remote Blynk dashboard to confirm synchronization and data integrity.

Although no external calibrated reference meter was used in this initial validation, the measured values were compared with typical electrical characteristics of 9 V batteries and standard LEDs as reported in the literature. Future work will

include formal accuracy and uncertainty analysis using calibrated instrumentation.

III. RESULTS

The experimental performance of the IoT DC smart power meter prototype was evaluated in a controlled laboratory environment at the Physics Laboratory, Federal Polytechnic Oko, Nigeria. The system was powered by a 9 V heavy-duty battery, and various LED loads (red, green, blue, white) were used to represent different electrical load profiles. The INA219 sensor module recorded bus voltage, load current, and computed power; the SSD1306 OLED display presented these parameters locally; and the same data were transmitted over Wi-Fi to the Blynk cloud dashboard for remote monitoring.

A. Baseline Measurement Validation

The SteadyState performance of the prototype was assessed using a red LED as the baseline test load. The measured electrical parameters are summarized in Table II.

Table II Summary of Measured Electrical Parameters Under Baseline Test Load.

Parameter	Measured Value	Expected Range	Remarks
Voltage (V)	8.94 V	8.50 – 9.20 V	Within normal 9 V battery operating range
Current (I)	15.10 mA	10.00 – 20.00 mA	Typical forward current for 5 mm LED load
Power (P)	0.13 W	0.10 – 0.20 W	Derived via $P = V \times I$

The measured bus voltage of 8.94 V lies within the nominal operating region of a fresh 9 V battery. The corresponding current of 15.10 mA and computed power of 0.13 W are consistent with typical forward-current characteristics of standard 5 mm LEDs. Power values were calculated from unrounded sensor readings; displayed voltage and current values are rounded to two decimal places. These baseline values agree with expected consumption profiles for low-power electronic monitoring applications reported in the energy submetering literature [24].

B. Dynamic Time-Series Analysis and Battery Discharge

To evaluate measurement stability and dynamic tracking capability, time-series data were collected over a 60-second interval at 10-second sampling intervals under a constant LED load. The results are presented in Table III.

Table III Time-Series Measurement of Voltage, Current, and Power Over a 60-Second Discharge Period.

Time (s)	Voltage (V)	Current (mA)	Power (W)
0	8.94	15.10	0.13
10	8.92	14.95	0.13
20	8.90	14.80	0.13
30	8.88	14.70	0.13
40	8.85	14.60	0.13
50	8.83	14.50	0.13
60	8.80	14.40	0.13

Over the 60-second observation window, the terminal voltage decreased linearly from 8.94 V to 8.80 V, while the current load declined from 15.10 mA to 14.40 mA, corresponding to a total current drop of 0.70 mA. The monotonic decrease in voltage and current reflects gradual battery discharge under a fixed load. This behaviour is illustrated in Fig. 3. The absence of abrupt spikes or erratic variations in the recorded samples indicates stable sensor operation and reliable I²C communication during the test. The observed discharge pattern is qualitatively consistent with behaviors reported in off-grid solar energy monitoring systems [20].

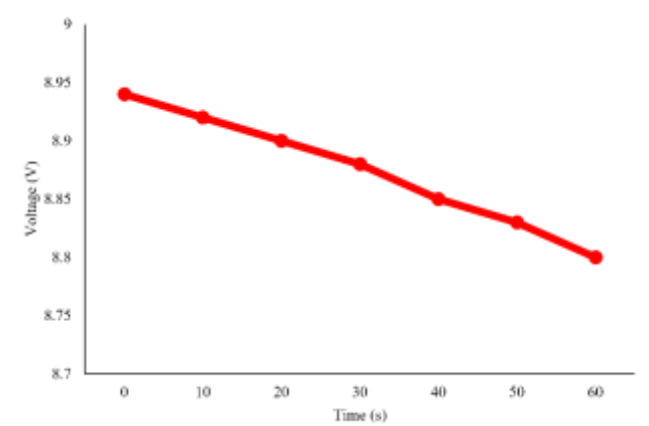


Fig. 3 Linear battery voltage discharge trajectory over a 60-second observation interval.

The computed power remained approximately 0.13 W throughout the test, consistent with the product of the measured voltage and current at each time step within rounding to two decimal places.

C. Comparative Semiconductor Load Profiling

To assess the sensor’s resolution across different electrical loads, four LED types with distinct semiconductor bandgaps (red, green, blue, white) were tested. The measured parameters for each load are shown in Table IV.

Table IV Comparative Electrical Parameter Measurements Across Different LED Loads.

LED Color	Voltage (V)	Current (mA)	Power (W)
Red	8.94	15.10	0.13
Green	8.92	14.80	0.13
Blue	8.90	16.20	0.14
White	8.88	16.50	0.15

The cooler-wavelength LEDs (blue and white) drew higher currents (16.20 mA and 16.50 mA) and consumed more power (0.14 W and 0.15 W) than the warmer-wavelength LEDs (red and green at 15.10 mA and 14.80 mA). This behavior is consistent with the higher forward voltage requirements of wide-bandgap semiconductor materials (InGaN-based blue/white LEDs) compared with narrower-bandgap materials (GaAsP-based red/green LEDs). These trends are shown in Fig. 4. The system was able to resolve current differences on the order of 0.30 mA between load states, indicating sufficient resolution for basic load profiling and energy-efficiency assessments in low-power DC networks [8].

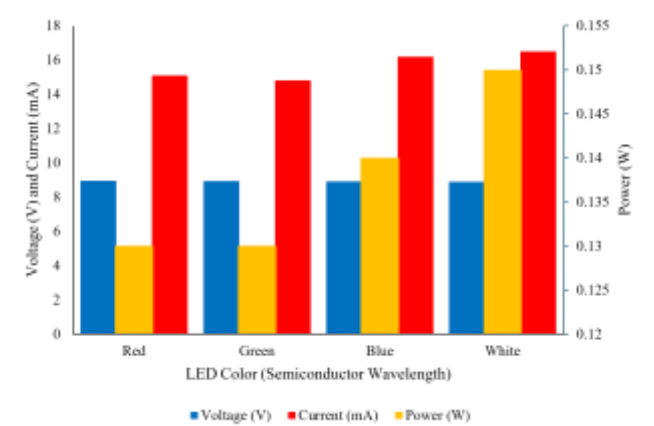


Fig. 4 Comparative current consumption profile across distinct LED semiconductor loads.

D. IoT Telemetry and Cloud Dashboard Synchronization

The data routing performance between the ESP32 microcontroller and the Blynk cloud server was evaluated over Wi-Fi. The virtual pin mapping and update intervals are summarized in Table V.

Table V Blynk IoT Cloud Telemetry Mapping and Update Intervals.

Parameter	Virtual Pin	Transmitted Value	Update Interval (s)
Bus Voltage	V0	8.72 V	1.0
Load Current	V1	14.50 mA	1.0
Calculated Power	V2	0.13 W	1.0

The parameter values displayed on the local SSD1306 OLED screen were observed to match closely with those shown on the Blynk cloud dashboard (e.g., 8.72 V $\rightarrow$ 8.7 V, 14.50 mA $\rightarrow$ 14.5 mA, 0.13 W $\rightarrow$ 0.1 W). This agreement confirms that the payload packaging and wireless transmission to the cloud preserved the measured data with negligible distortion. This agreement is illustrated in Fig. 5. The update interval of approximately 1.0 s provided near-real-time visibility of the electrical parameters on the remote dashboard. The configured full-scale gauge limits on the Blynk dashboard (26 V, 3,200 mA, 80 W) align with the maximum measurement specifications of the INA219 module, indicating that the architecture can accommodate higher-power DC loads without fundamental changes to the hardware or firmware [5,10]. The dashboard displayed the calculated power to one decimal place, whereas the local value was recorded to two decimal places.



(a) Local SSD1306 OLED display (b) Blynk IoT cloud dashboard

Fig. 5 Real-time dual-tier telemetry synchronization showing identical parameter readings across (a) the physical SSD1306 OLED hardware display and (b) the remote Blynk IoT cloud mobile dashboard interface.

IV. DISCUSSION

A. Interpretation of Experimental Findings

The experimental results demonstrate the functional effectiveness, measurement consistency, and telemetry reliability of the proposed low-cost IoT DC smart power meter. The INA219 high-side current and voltage sensor proved suitable for low-voltage DC monitoring. Its internal 12-bit ADC and onboard 0.1 Ω shunt resistor eliminated the need for external amplification or complex analog signal-conditioning circuitry. Under the baseline test condition with a red LED load, the system measured a bus voltage of 8.94 V, a load current of 15.10 mA, and a computed power of 0.13 W. These values are consistent with the expected electrical characteristics of a 9 V battery driving a standard 5 mm LED. The results confirm that low-cost embedded systems can provide sufficiently stable data acquisition for real-time monitoring and basic resource optimization in small-scale DC applications [2].

The time-series measurements in Table III show that the prototype can track gradual electrical variations under a sustained load. Over the 60-second observation period, the terminal voltage decreased from 8.94 V to 8.80 V, while the

current declined from 15.10 mA to 14.40 mA. This monotonic discharge pattern is consistent with the behavior of a finite-capacity battery under constant load and is qualitatively similar to trends reported in off-grid solar energy monitoring systems. The absence of abrupt spikes or erratic variations in the recorded samples indicates stable sensor operation and reliable I²C communication during the test [20]. The comparative load profiling in Table IV further highlights the resolution of the meter. The system distinguished differences in current consumption among LEDs of different wavelengths: cooler-wavelength devices (blue at 16.20 mA and white at 16.50 mA) drew more current and power than warmer-wavelength devices (red at 15.10 mA and green at 14.80 mA). This behaviour aligns with semiconductor bandgap physics, where wide-bandgap materials (InGaN-based blue/white LEDs) require a higher forward voltage threshold to achieve conduction compared with narrower-bandgap materials (GaAsP-based red/green LEDs). The ability to resolve current differences on the order of 0.30 mA suggests that the prototype is suitable for basic load profiling and energy-efficiency assessments in low-power DC networks [8].

The dual-tier telemetry results (Fig. 5) show close agreement between the local OLED display and the remote Blynk dashboard (e.g., 8.72 V $\rightarrow$ 8.7 V, 14.50 mA $\rightarrow$ 14.5 mA, 0.13 W $\rightarrow$ 0.1 W). This correspondence confirms that the data transmitted over Wi-Fi preserved the measured values with negligible distortion and that the update interval of approximately 1.0 s provides near-real-time visibility of the electrical parameters.

B. Comparison with Prior Works

The proposed system targets low-voltage DC microgrids using an INA219 high-side shunt sensor and a 12-bit ADC integrated within the sensor module, combined with dual-tier telemetry (local OLED display and Blynk cloud dashboard) at approximately 1 s update intervals. This design emphasizes ultra-low component cost (~₦20,000 / ~\$14.60), fine current resolution, and replicability for educational and diagnostic applications.

In contrast, Ezhilarasi *et al.* and Chong focus primarily on alternating current (AC) prepaid and household grids [7]. Their architectures employ custom AC sampling circuits or standard AC sensors/current transformers, together with microcontroller-based processing. While these systems demonstrate viable smart metering concepts for utility AC networks, they are not optimized for low-voltage DC micro-grid conditions and generally involve higher hardware costs than the present prototype. Moreover, their telemetry schemes are either limited to local prepayment interfaces or implemented as cloud-only solutions without synchronized local visualization.

Gajera *et al.* presents a DC-centric energy meter based on analog shunt and divider circuitry with external ADC or microcontroller processing [14]. Although their work addresses DC renewable applications, it does not integrate a

low-latency cloud telemetry framework or dual-tier visualization as implemented in this study. The present prototype therefore extends prior DC metering efforts by combining a high-resolution integrated sensor (INA219), a low-cost ESP32 platform, and simultaneous local and cloud monitoring within a single compact design.

Collectively, these comparisons highlight that the proposed system fills a specific niche: an inexpensive, open-hardware DC power meter with sufficient resolution for low-power loads and integrated IoT telemetry, suitable for educational laboratories, decentralized DC micro-grid diagnostics, and preliminary off-grid solar PV monitoring.

C. Practical Implications and Applications

The successful implementation of this low-cost, cloud-integrated DC power meter offers several practical benefits:

1. **Renewable Energy and Microgrids:** Since solar PV systems and battery storage operate natively in DC, direct DC metering avoids conversion losses and provides accurate generation and consumption telemetry for off-grid communities and renewable microgrids [4].
2. **Education and Training:** The low component cost and open-hardware design make the prototype suitable as an instructional kit for teaching embedded systems, sensor interfacing, and IoT telemetry in polytechnics and universities.
3. **Diagnostics for Low-Power DC Systems:** The sub-milliampere current resolution enables fine-grained diagnostics for battery banks, telecom backup power, and low-power IoT sensor nodes, where small current variations are significant [6].

These applications align with broader efforts to improve energy visibility, efficiency, and management in decentralized and off-grid contexts.

D. System Limitations

Despite its demonstrated functionality, the prototype has several technical limitations:

1. **Measurement Range:** The default hardware configuration, with a $0.1\ \Omega$ shunt resistor, limits measurable parameters to approximately 26 V DC and $\pm 3.2\ \text{A}$. Monitoring higher-power DC loads would require replacing the onboard shunt with a lower resistance value (e.g., $0.01\ \Omega$) and recalibrating the measurement range.
2. **Dependence on Wi-Fi Connectivity:** Cloud telemetry relies on continuous 2.4 GHz Wi-Fi connectivity. Network disruptions will interrupt cloud updates, although local OLED monitoring remains operational. Future designs could incorporate onboard storage (e.g., SPI flash or microSD) to buffer data during connectivity outages.
3. **Preliminary Validation:** The current evaluation is based on a limited set of load conditions and does not include formal accuracy and uncertainty analysis against

calibrated reference instruments. Subsequent work should quantify measurement error, repeatability, and long-term stability under diverse environmental and load conditions.

Acknowledging these limitations clarifies the appropriate scope of application for the present prototype and provides a basis for targeted improvements in future iterations.

V. CONCLUSION

This work presented the design, implementation, and experimental validation of an ultra-low-cost, IoT-enabled smart power meter for low-voltage direct current (DC) applications. The prototype integrates an ESP32 microcontroller with an INA219 high-side current and voltage sensor over an I²C bus, a local SSD1306 OLED display, and Wi-Fi-based telemetry to the Blynk cloud platform. The system was evaluated using a 9 V battery source and multiple LED load configurations.

The empirical evaluations confirmed the following key outcomes:

1. Under a baseline test load, the system measured a bus voltage of 8.94 V, a load current of 15.10 mA, and a computed power of 0.13 W, all within the expected ranges for small-scale DC circuits powered by a 9 V battery.
2. Time-series tracking over a 60-second operational window resolved a linear voltage drop from 8.94 V to 8.80 V and a corresponding current decrease from 15.10 mA to 14.40 mA during battery discharge, demonstrating stable sensor operation without observable measurement jitter.
3. Comparative load profiling across distinct LED semiconductor wavelengths showed that the system can resolve current differences on the order of 0.30 mA, capturing higher power consumption in wider-bandgap LEDs (blue/white at 0.14–0.15 W) compared with narrower-bandgap LEDs (red/green at 0.13 W).
4. Dual-tier telemetry successfully mirrored local SSD1306 OLED display readings onto the remote Blynk IoT cloud dashboard with an update interval of approximately 1.0 s over Wi-Fi.

The proposed system constitutes a replicable, open-hardware platform that bridges the gap between expensive commercial metering equipment and low-resolution basic prototypes. Its low component cost (~₦20,000 / ~\$14.60) makes it an affordable foundation for educational physics and electronics laboratories, decentralized DC microgrid diagnostics, off-grid solar PV monitoring, and localized energy auditing.

A. Recommendations and Future Work

Based on the technical limitations and experimental findings, the following directions are recommended for future research and development:

1. Future iterations should evaluate higher-power DC loads such as DC motors, thermoelectric coolers, and solar PV charge controllers. To extend the current measurement

range beyond the default ± 3.2 A limit, the onboard $0.1\ \Omega$ shunt resistor of the INA219 can be replaced with a lower resistance value (e.g., $0.01\ \Omega$) and the measurement range recalibrated.

2. To ensure continuous data logging during Wi-Fi outages, an onboard storage mechanism (e.g., SPI flash using LittleFS or a microSD card module) should be integrated to buffer time-series metrics locally until cloud connectivity is restored.
3. Firmware functionality can be enhanced by integrating relay modules and Blynk push-notification triggers to implement active load shedding and user alerts when battery voltage falls below a critical threshold or when over-current conditions are detected.
4. Future software revisions should incorporate continuous watt-hour (Wh) accumulation and automated billing estimators within the ESP32 code to support real-time tariff calculations in decentralized micro-DC energy distribution networks.

These enhancements would extend the prototype from a monitoring and educational tool toward a more comprehensive energy management and metering solution for practical low-voltage DC systems.

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