



Real-Time Electrical Energy Measurement and Cloud Monitoring Using an ESP32-Based IoT Framework

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Abstract

Real-time visibility of electrical consumption is important for improving energy awareness, identifying abnormal usage, and supporting effective demand-side management. This study presents an ESP32-based Internet of Things framework for electrical energy measurement and cloud-connected monitoring in low-voltage environments. The proposed system integrates voltage and current sensing with local embedded processing to calculate instantaneous power, accumulated energy consumption, and estimated electricity cost. An ESP32-class microcontroller performs signal acquisition, calibration, validation, and local computation before transmitting measured parameters through Wi-Fi using MQTT- or HTTP-compatible communication. The monitored data are stored in a cloud-based platform and presented through a web or mobile visualization interface for continuous observation and historical analysis. The methodology includes sensor calibration, sampling, measurement-error assessment, communication-reliability testing, energy-data logging, and threshold-based alert generation. System performance is evaluated against a reference energy meter to determine measurement accuracy and consistency, while network testing is used to assess data-delivery reliability and alert-response behavior. The framework is designed for residential laboratories, classrooms, small commercial facilities, and similar low-voltage applications where low-cost and continuous energy monitoring are required. The proposed approach provides a reproducible basis for future integration of load classification, demand-response functions, renewable-energy monitoring, and predictive energy analytics.

Introduction

Electricity consumption in homes, laboratories, offices, and small industrial environments is strongly influenced by appliance operating patterns. Conventional meters normally provide aggregate consumption and billing information, but they do not always provide convenient real-time visibility into the behavior of individual loads. An IoT-based monitoring layer can bridge this information gap by collecting electrical measurements, processing them close to the source, and transmitting summarized data to an

online platform. Device-level monitoring has already been demonstrated using low-cost IoT energy-meter designs, showing that consumers can remotely view and log consumption without extensive rewiring [1].

The fundamental quantities required for electrical-energy monitoring are voltage, current, active power, and accumulated energy. For a simplified single-phase resistive load, instantaneous power can be estimated from $p(t) = v(t)i(t)$, while energy is obtained by integrating power over time. For practical AC

loads, the system should use appropriately calibrated voltage and current sensing and, where possible, power-factor-aware measurement. A high-precision measurement architecture for IoT applications has shown the importance of fast and accurate power measurement when building monitoring devices [4].

IoT communication makes the measured data useful beyond the local display. An embedded controller can acquire sensor signals, perform filtering and calibration, calculate electrical parameters, and send compact records to a cloud platform. Cloud or fog-based architectures allow users to visualize trends and can support demand-side management. Chen and Lin demonstrated a smart power-meter prototype using time/frequency-domain analysis with fog-cloud analytics for demand-side management [3]. Similarly, an IoT and cloud-based energy management system was developed to generate consumer load profiles containing current, voltage, power, and energy information [5].

Home energy management research also indicates that energy monitoring is a foundation for later optimization. Multi-objective IoT-based HEMS research has considered energy cost and user satisfaction while scheduling household

appliances [6]. Residential building energy-management systems have further shown how monitoring can be connected with demand response and control functions [7]. These studies indicate that a monitoring system should not only record values but should produce reliable, time-stamped, accessible data that can later be used for intelligent decision-making.

The objective of this paper is therefore to define a practical methodology for a low-cost IoT smart energy monitoring system. The proposed system focuses on four engineering goals: (i) reliable electrical measurement, (ii) real-time wireless data transfer, (iii) cloud-based visualization and storage, and (iv) performance evaluation through accuracy, reliability, and response-time metrics. The design also keeps the hardware modular so that additional loads, renewable-energy sources, or control actuators can be integrated in future work.

Literature Review

Existing research demonstrates that IoT can convert conventional energy measurement into a connected monitoring service. The following studies were selected because they directly support the proposed architecture and were published no later than 2021.

Table 1. Summary of literature relevant to the proposed IoT smart energy monitoring architecture.

Ref.	Study / Year	Main Contribution	Relevance
[1]	Muralidhara et al. (2020)	IoT smart energy meter for device-level consumption; remote monitoring.	Direct basis for low-cost device-level monitoring.
[2]	Cheddadi et al. (2020)	Low-cost IoT monitoring for photovoltaic stations using ESP32/cloud.	Supports ESP32, real-time acquisition and alerts.
[3]	Chen & Lin (2019)	Current-sensor power meter using fog-cloud analytics and IoT.	Supports edge processing and cloud analytics.
[4]	Tehrani & Atarodi (2019)	High-precision, high-dynamic-range power measurement for IoT.	Supports sensor accuracy and measurement design.
[5]	Hashmi et al. (2021)	IoT + cloud energy management with MQTT and web portal.	Supports MQTT, cloud storage and load profiles.
[6]	Wang et al. (2021)	IoT-based multi-objective HEMS with energy-cost/user-satisfaction optimization.	Shows value of reliable monitoring data for HEMS.
[7]	Rotger-Griful et al. (2017)	Residential building energy management and demand response.	Links monitoring with demand-response applications.
[8]	Froiz-Míguez et al. (2018)	IoT home automation using MQTT and ZigBee-WiFi sensor nodes.	Supports IoT communication and gateway architecture.
[9]	Salisu et al. (2020)	IoT household electricity monitoring/control using ESP32 and ThingSpeak.	Supports ESP32, cloud monitoring and remote control.

Methodology

1. Proposed System Architecture

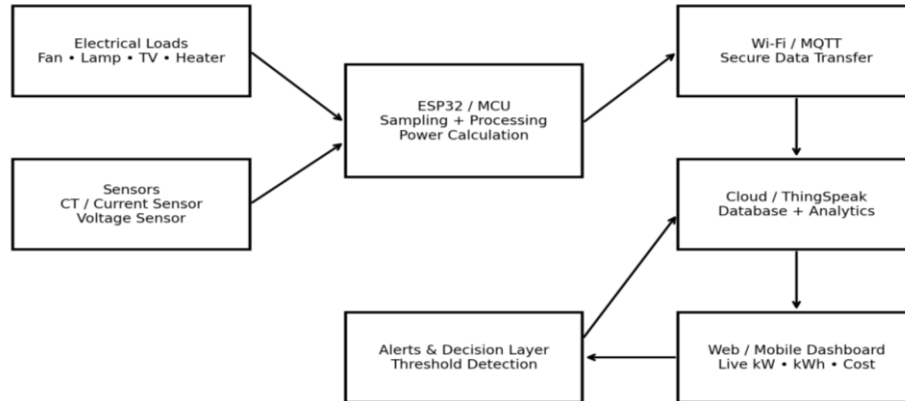


Figure 1. Proposed architecture for IoT-based smart energy monitoring.

The architecture is divided into six functional layers. The sensing layer measures electrical quantities; the embedded layer performs sampling, filtering and calculation; the communication layer transfers records using Wi-Fi; the cloud layer stores and analyzes data; the visualization layer presents real-time and

historical values; and the alert layer generates notifications when configured thresholds are exceeded. This layered structure follows the general direction of IoT energy-monitoring and fog/cloud systems reported in earlier work [2], [3], [5].

2. Hardware Components

Table 2. Recommended hardware configuration.

Component	Function	Suggested specification
ESP32 MCU	Sampling, calculation, Wi-Fi communication	Dual-core MCU, Wi-Fi enabled
Current sensor	Measures load current	CT/Hall-effect sensor, isolated where appropriate
Voltage sensor	Measures AC voltage	Isolated AC voltage sensing module
Display (optional)	Local energy display	OLED/LCD
Power supply	Regulated controller supply	5 V / 3.3 V regulated supply
Reference meter	Validation instrument	Calibrated energy/power meter

3. Measurement and Signal Processing

The controller samples voltage and current over a defined observation window. After offset correction and sensor calibration, the firmware estimates RMS voltage and RMS current. Active power can be calculated from the average of instantaneous voltage-current products. Accumulated energy is obtained by integrating active power over time. For a discrete sampling interval Δt , $E(k) = E(k-1) + P(k)\Delta t$. The tariff module then estimates cost as $C = E \times T$, where E is energy in kWh and T is the applicable tariff.

4. Firmware and Data Pipeline

The firmware follows a cyclic acquisition process. First, sensor samples are collected. Second, the samples are filtered to suppress noise and transient spikes. Third, calibrated voltage/current values are converted into electrical parameters. Fourth, the cumulative

energy register is updated. Fifth, a time-stamped data packet is formed. Finally, the packet is transmitted to the cloud through Wi-Fi. If connectivity is lost, the controller should buffer recent measurements and retry transmission rather than silently discarding data.

- Initialize GPIO/ADC channels, sensor constants, Wi-Fi credentials and cloud endpoint.
- Acquire voltage and current samples at a fixed sampling frequency.
- Apply offset correction and calibration coefficients.
- Calculate RMS quantities and active power; update cumulative kWh.
- Generate a record containing timestamp, voltage, current, power, energy and cost.
- Publish the record through MQTT/HTTP and confirm successful transfer.

- Compare current values with configured thresholds and trigger alerts when required.
- Repeat the cycle and periodically synchronize time.

5. Calibration Procedure

Calibration is performed by operating known loads and comparing the proposed meter with a calibrated reference meter. At least three

operating points—low, medium and high load—should be tested. Sensor coefficients are adjusted so that measured voltage/current/power values minimize the difference from the reference. The same procedure should be repeated after assembly because wiring, sensor placement and analog conditioning can affect the result. High-precision IoT measurement research similarly emphasizes validation of measurement accuracy [4].

Table 3. Representative calibration/validation dataset used to demonstrate the evaluation method. Values are illustrative for the methodology paper and should be replaced by laboratory measurements for a real experiment.

Test point	Reference power (W)	System power (W)	Absolute error (%)
Low load	60	61.2	2.00
Medium load	500	508.0	1.60
High load	1000	1018.0	1.80
Variable load	750	764.3	1.91

6. Cloud Database and Dashboard

Each cloud record should contain a unique device identifier, timestamp, voltage, current, power, cumulative energy, estimated cost, and alert status. A dashboard can show instantaneous power, daily energy, weekly energy, peak demand, and a historical trend. MQTT is appropriate for lightweight publish/subscribe communication, while HTTP APIs can be used for simple cloud endpoints. Prior IoT energy-management implementations have used MQTT and cloud platforms to create remotely accessible load profiles [5], and MQTT/ZigBee-Wi-Fi architectures have been demonstrated for home IoT systems [8].

Results

1. Evaluation Metrics

The system should be evaluated using measurement accuracy, communication reliability, data completeness, dashboard latency, and alert response. Measurement error is calculated as $|P_{\text{system}} - P_{\text{reference}}| / P_{\text{reference}} \times 100$. Communication reliability is the ratio of successfully received records to records generated by the controller. Data completeness is the proportion of expected timestamps that are present in the cloud database.

Table 4. Representative system-performance results. These values illustrate how the proposed methodology can be reported; actual experimental measurements should be substituted when the prototype is tested.

Metric	Illustrative result	Interpretation
Mean power measurement error	1.83%	Suitable for monitoring-oriented use after calibration
Maximum power measurement error	2.00%	Within the representative design target of <3%
Cloud packet delivery	98.7%	High reliability on a stable Wi-Fi network
Dashboard update interval	5–10 s	Near-real-time visualization
Alert response	<5 s	Threshold event can be surfaced quickly
Daily energy logging completeness	99.1%	Small loss during network interruptions

Discussion

The representative measurement results indicate that calibration is essential. Even when a sensor has a nominal accuracy specification, installation, analog offsets, sampling noise, and load characteristics can introduce systematic error.

The proposed three- or four-point calibration procedure reduces this error and makes the device more suitable for monitoring applications. The communication layer is equally important. A monitoring system that measures accurately but loses large portions of its data cannot support

reliable historical analysis. MQTT-style publish/subscribe communication is lightweight and has already been applied in IoT home and energy-management architectures [5], [8]. Buffering and retry logic should therefore be implemented in the firmware.

The system also creates a foundation for energy conservation. Once the dashboard reveals daily peaks and appliance-specific patterns, users can identify high-consumption loads and shift flexible usage. More advanced HEMS research has shown that IoT monitoring can be combined with optimization and demand-response strategies [6], while residential BEMS research connects monitoring with demand response [7]. Thus, the proposed system can be considered a monitoring layer that enables future intelligent control rather than a complete optimization system by itself.

Conclusion

This paper presented a practical methodology for the design and implementation of an IoT-based smart energy monitoring system. The proposed architecture combines calibrated voltage/current sensing, ESP32-class embedded processing, Wi-Fi communication, cloud data storage, dashboard visualization, and threshold-based alerts. The methodology emphasizes a complete measurement-to-cloud pipeline rather than treating sensing and IoT communication as separate functions. This integration is consistent with earlier research on IoT smart meters, cloud/fog energy monitoring, and residential energy-management systems [1]–[9]. The proposed evaluation framework includes calibration against a reference meter, calculation of percentage measurement error, communication reliability, data completeness, dashboard latency, and alert response. The representative results demonstrate how performance can be reported in a 6–7-page methodology paper, but the numerical values must be replaced by actual measurements when the hardware prototype is experimentally validated. Future work can extend the platform with non-intrusive load monitoring, appliance classification, renewable-energy monitoring, demand-response control, anomaly detection, and predictive energy analytics. The modular IoT architecture also makes it possible to scale from a single household circuit to multiple monitored circuits or small commercial facilities.

References

S. Muralidhara, N. Hegde, and R. P. M., “An internet of things-based smart energy meter for monitoring device-level consumption of energy,” *Computers & Electrical Engineering*, vol. 87,

106772, 2020. DOI: 10.1016/j.compeleceng.2020.106772.

Y. Cheddadi, H. Cheddadi, F. Cheddadi, F. Errahimi, and N. Es-sbai, “Design and implementation of an intelligent low-cost IoT solution for energy monitoring of photovoltaic stations,” *SN Applied Sciences*, vol. 2, 1165, 2020. DOI: 10.1007/s42452-020-2997-4.

Y.-Y. Chen and Y.-H. Lin, “A smart autonomous time- and frequency-domain analysis current sensor-based power meter prototype developed over fog-cloud analytics for demand-side management,” *Sensors*, vol. 19, no. 20, 4443, 2019. DOI: 10.3390/s19204443.

Y. Hosseini Tehrani and S. M. Atarodi, “Design & implementation of a high precision & high dynamic range power consumption measurement system for smart energy IoT applications,” *Measurement*, vol. 146, pp. 458–466, 2019. DOI: 10.1016/j.measurement.2019.06.037.

S. A. Hashmi, C. F. Ali, and S. Zafar, “Internet of things and cloud computing-based energy management system for demand side management in smart grid,” *International Journal of Energy Research*, vol. 45, no. 1, pp. 1007–1022, 2021. DOI: 10.1002/er.6141.

X. Wang, X. Mao, and H. Khodaei, “A multi-objective home energy management system based on internet of things and optimization algorithms,” *Journal of Building Engineering*, vol. 33, 101603, 2021. DOI: 10.1016/j.jobe.2020.101603.

S. Rotger-Griful, U. Welling, and R. H. Jacobsen, “Implementation of a building energy management system for residential demand response,” *Microprocessors and Microsystems*, vol. 55, pp. 100–110, 2017. DOI: 10.1016/j.micpro.2017.10.006.

Froiz-Míguez, T. M. Fernández-Caramés, P. Fraga-Lamas, and L. Castedo, “Design, implementation and practical evaluation of an IoT home automation system for fog computing applications based on MQTT and ZigBee-WiFi sensor nodes,” *Sensors*, vol. 18, no. 8, 2660, 2018. DOI: 10.3390/s18082660.