

## Smart Energy Meter Using IOT and Offline Data Storage

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**Abstract**— Traditional electromechanical and basic digital meters offer limited visibility into consumption patterns, are prone to manual reading errors, and provide no proactive protection against abnormal electrical conditions. This work presents a low-cost, IoT-enabled smart energy meter that delivers real-time monitoring, anomaly detection, and automated protection while maintaining reliable operation during network outages. The prototype integrates a NodeMCU ESP8266 microcontroller with a ZMPT101B voltage sensor and an ACS712 current sensor to compute RMS voltage/current, active power, and cumulative energy. A lightweight embedded pipeline performs signal conditioning and measurement, triggers over/undervoltage events, and actuates a load cut-off relay for safety. To ensure data continuity, the system adopts an offline-first strategy: measurements are cached in on-board non-volatile memory (EEPROM) when connectivity is unavailable and automatically synchronized to a cloud dashboard once the link is restored. The cloud layer enables live visualization, threshold-based alerts, and remote oversight suitable for residential and small commercial use. The design emphasizes affordability, ease of deployment, and modularity, making it adaptable to diverse installation contexts. Prototype evaluation under common household load profiles confirms stable measurement, timely protection actuation, and seamless data reconciliation after connectivity loss, indicating practical readiness for smart metering, energy awareness, and streamlined utility engagement.

**Keywords**— Smart energy meter, Internet of Things (IoT), ESP8266 (NodeMCU), ACS712 current sensor, ZMPT101B voltage sensor, Real-time energy monitoring, EEPROM, Overvoltage/undervoltage protection, Automated load cut-off, Offline data storage, Cloud integration

### I. INTRODUCTION

Residential and small-commercial electricity use is becoming more variable and data-driven as households adopt high-efficiency appliances, rooftop solar, and home automation. Yet the metering infrastructure in many settings still relies on devices that provide only cumulative readings and require manual collection. Without fine-grained, timely data, users struggle to understand when and where they consume the most energy, and utilities cannot detect anomalies or voltage quality issues until after they have

caused equipment wear, tripped protection devices, or inflated bills. This gap is especially problematic in environments with intermittent connectivity or unreliable power, where continuous telemetry is most valuable but hardest to maintain.

Low-cost microcontrollers with built-in Wi-Fi have made it feasible to place intelligence at the edge of the electrical system. By sampling voltage and current locally, computing power and energy in real time, and streaming results to a dashboard, these platforms can turn a meter into an active monitoring and protection device. However, two practical hurdles limit the usefulness of many prototypes in real-world homes and small businesses. First, they often assume persistent network availability. When Wi-Fi or backhaul fails—due to router resets, ISP outages, or simply weak signal—data are dropped, creating blind spots that undermine analytics, billing reconciliation, and user trust. Second, metering and visualization are frequently implemented without integrated electrical protection, leaving end-equipment exposed to sustained overvoltage or undervoltage events that could have been mitigated by automated disconnection and timely alerts.

This work addresses those gaps with a design that combines reliable measurement, offline-first data handling, and built-in protection in an affordable, reproducible package. The proposed system uses a Wi-Fi-enabled microcontroller to acquire voltage and current through low-cost sensors, compute RMS values, active power, and cumulative energy, and enforce configurable safety thresholds in real time. When the measured voltage strays outside acceptable bounds or when abnormal consumption patterns are detected, the controller actuates a relay to isolate the load, preventing damage while recording the event for later analysis. To maintain a continuous record, the meter buffers timestamped measurements and events in non-volatile memory whenever connectivity is unavailable. Once the network is restored, the device automatically synchronizes its backlog to the cloud, preserving the chronological sequence so dashboards and analytics remain complete.

Several design choices support robust field operation. Signal conditioning and sampling parameters are tuned for mains frequency to obtain stable RMS estimates while keeping computation and energy use low. A lightweight firmware pipeline separates acquisition, calculation, rule evaluation, and storage so that no single task blocks the rest, even during extended outages. Calibration routines and coefficients are stored on-device to correct for sensor offsets and scaling drift. At the system level, the architecture remains modular: different current or voltage sensing modules can be swapped in as accuracy or range requirements change, and the cloud interface can target MQTT or HTTPS endpoints without altering the core metering logic. This modularity makes the approach adaptable to varied installation contexts, from single-circuit residential sub-metering to small shops with several monitored branches.

Beyond monitoring and protection, the project emphasizes usability and cost. The bill of materials is intentionally lean, favoring widely available components and straightforward assembly. The user interface exposes key metrics—voltage, current, power, energy, and status of protection—in a web or mobile dashboard, with threshold-based notifications to surface actionable events rather than raw data alone. By balancing accuracy, responsiveness, and affordability, the system is designed to serve as both a practical tool for end users and a platform for further research on demand response, appliance-level disaggregation, and grid-edge analytics.

The contributions of this paper are threefold. First, it presents a low-cost, IoT-enabled smart meter that integrates real-time measurement with automated over/undervoltage protection. Second, it introduces an offline-first data pipeline that guarantees continuity during connectivity loss and supports seamless, ordered synchronization to the cloud once connectivity returns. Third, it demonstrates the practicality of the design through prototype evaluation under typical household load profiles, highlighting stable measurements, timely protection actuation, and lossless data reconciliation. Together, these elements advance a pragmatic path toward smarter, safer, and more transparent energy use in environments where reliability and budget matter.

The remainder of the paper details the system architecture and hardware selection, describes the firmware and data-handling methods, presents calibration and testing procedures, evaluates performance under representative scenarios, and discusses limitations and future extensions, including enhanced metrology options, security hardening, and integration with utility billing workflows.

## II. BACKGROUND AND RELATED WORK

Smart metering has evolved from electromechanical counters to electronic meters with automated reading, utility backhaul, and limited analytics. Early deployments focused on remote

billing (AMR) and later on bidirectional communication and control (AMI). More recently, low-cost embedded platforms and ubiquitous Wi-Fi have pushed intelligence to the edge, enabling real-time monitoring, event detection, and user-facing feedback within homes and small businesses. This shift reframes the meter from a passive recorder to an active node that can sense, decide, and act locally while synchronizing with cloud services.

**IoT platforms for metering:** Affordable microcontrollers with integrated networking (e.g., ESP8266/ESP32) have become popular in research prototypes and maker projects due to their cost, community support, and sufficient processing for mains-synchronous sampling and on-device computation. Compared with cellular or LPWAN modules, Wi-Fi suits indoor residential deployments where existing infrastructure is available and latency requirements are modest. Studies and open implementations commonly pair these MCUs with lightweight protocols (MQTT or HTTPS) and simple JSON payloads for telemetry, configuration, and alerting. The trade-offs are clear: Wi-Fi simplifies setup and dashboarding but introduces dependency on local network quality and higher power draw than sub-GHz alternatives.

**Sensing and metrology approaches:** At the sensing layer, three current-sensing strategies dominate low-cost designs: Hall-effect modules (e.g., ACS712), current transformers (CTs), and shunt resistors with precision amplifiers. Hall sensors offer galvanic isolation, compact form factor, and ease of integration but require calibration to mitigate offset drift and temperature effects. CTs provide natural isolation and good linearity for AC loads but need burden resistor selection and careful phase compensation. Shunts enable high accuracy and DC measurement at very low cost, but they demand robust isolation and thermal management. For voltage measurement, options include resistive dividers with proper isolation and transformer-based modules such as ZMPT101B to improve safety and common-mode rejection. Across these options, calibration—both gain and offset—is essential to achieve practical accuracy for RMS voltage/current, active power, and accumulated energy.

On-device computation typically samples near an integer multiple of the mains frequency (50/60 Hz) to stabilize RMS estimates and reduce spectral leakage. Sliding-window RMS, zero-crossing alignment, and simple digital filtering (e.g., moving average or low-order IIR) are often sufficient on resource-constrained MCUs. Active power is computed as the mean of instantaneous voltage-current products over one or more cycles, and energy as the time integral of active power. Designs that also estimate power factor or apparent power must account for phase shifts introduced by sensors and conditioning circuits; compensation can be performed during calibration.

Communication, dashboards, and control: Cloud-connected smart meters commonly publish time-stamped measurements to a broker or REST endpoint, where dashboards visualize trends, compute daily/weekly aggregates, and trigger alerts. MQTT is popular for its pub/sub model, low overhead, and QoS options; HTTPS works well when infrastructure favors REST and webhooks. Idempotent message design and unique sample identifiers help prevent duplication during retries. Remote control—such as turning loads on/off or adjusting thresholds—can be exposed via downlink topics or configuration endpoints, but this introduces security considerations, including secure credential storage, TLS, and update hygiene.

Offline-first and data continuity: Real homes and shops experience intermittent Wi-Fi, router restarts, and power events. Many published prototypes stream data continuously but omit robust strategies for lossless logging during outages. Offline-first designs buffer time-stamped measurements locally and reconcile them later. Storage choices include on-chip EEPROM/Flash, external SPI Flash or FRAM, and SD cards. Key engineering concerns are wear levelling (particularly for EEPROM/Flash), bounded memory footprint, and recovery logic that preserves chronological order without blocking real-time acquisition. Circular buffers, write-ahead logs, and compact binary records are common patterns. Accurate timekeeping under outages often requires a battery-backed RTC or deterministic resynchronization with NTP upon reconnect; when absolute time is unavailable, sequence numbers and relative timestamps enable ordered reconstruction on the server.

Protection and safety integration: While many IoT meters focus on monitoring and visualization, integrating electrical protection elevates practical value. Overvoltage/undervoltage detection with configurable thresholds and hysteresis can prevent nuisance trips and equipment damage. Actuation typically uses an electromechanical relay (cost-effective, clear isolation) or a solid-state relay (fast, silent, but with leakage and thermal considerations). Designs that switch near zero-cross reduce contact stress; debounce and minimum-off timers avoid rapid cycling. Protection functions should fail safe on firmware crashes or power anomalies, which motivates clear separation between sensing, decision logic, and actuation paths, as well as watchdogs and brownout handling.

**Related work landscape and gaps:** A large body of academic and hobbyist work demonstrates Wi-Fi smart meters built around ESP-class microcontrollers with commodity sensors for voltage and current. Many report successful real-time dashboards and basic alerting; some add local logging using EEPROM or SD to mitigate connectivity issues; others explore over/undervoltage cut-off to protect connected loads. However, several gaps persist across this landscape:

- A. Data continuity: Few low-cost designs provide a rigorous offline-first pipeline with wear-aware buffering, ordered backfill, and idempotent cloud sync that guarantees gap-free timelines after prolonged outages.
- B. Integrated protection with metrology: Protection logic is often bolted on rather than co-designed with the metering pipeline, leading to inconsistent response times, limited configurability, or brittle interactions during brownouts.
- C. Calibration and validation: Many reports provide limited detail on calibration against traceable references, long-term drift, temperature effects, or repeatability across units—factors that determine practical accuracy and reliability.
- D. Security and maintainability: Credential management, secure updates, and local fail-safe behavior are frequently under-specified, despite their importance for safe remote control and long-term field operation.
- E. Extensibility: Support for multi-channel or multi-phase measurement, tamper detection, and integration with utility workflows (e.g., prepaid/postpaid billing, tariff modeling) remains uncommon in lower-cost prototypes.

**Positioning of this work:** The present system is designed in response to these gaps. It combines low-cost sensing and ESP-class edge computing with an offline-first storage and synchronization strategy, and it integrates protection as a first-class function with deterministic thresholds, hysteresis, and actuation timing. The architecture emphasizes reproducibility: clearly defined sampling and computation pipelines, calibration storage, bounded and wear-conscious buffering, and a cloud interface that enforces ordered, idempotent ingestion. This positions the meter as both a practical tool for residential and small commercial settings and a platform for further research on reliability, protection, and analytics at the grid edge.

### III. SYSTEM OVERVIEW

This work implements a low-cost, IoT-enabled smart energy meter that measures mains voltage and current, computes RMS values and active power in real time, accumulates energy, enforces over/undervoltage protection via a relay, and supports reliable cloud synchronization using an offline-first buffer when connectivity drops. The design goals are:

- I. Reliability under intermittent connectivity: no data loss, ordered backfill, and idempotent uploads.
- II. Safety and protection: deterministic trip thresholds, hysteresis, minimum-off timers, and fail-safe behaviour.
- III. Accuracy within practical constraints: calibration for gain/offset and phase compensation for sensors.
- IV. Affordability and reproducibility: commodity parts, minimal BOM, and modular firmware.

Data flow at a glance:

- I. Edge sensing and computation at the ESP-class microcontroller.
- II. Event evaluation and protection actuation.
- III. Local persistence in a circular buffer (EEPROM/Flash).
- IV. Secure publish to a cloud endpoint (MQTT/HTTPS) with sequence-aware ingestion and dashboarding.

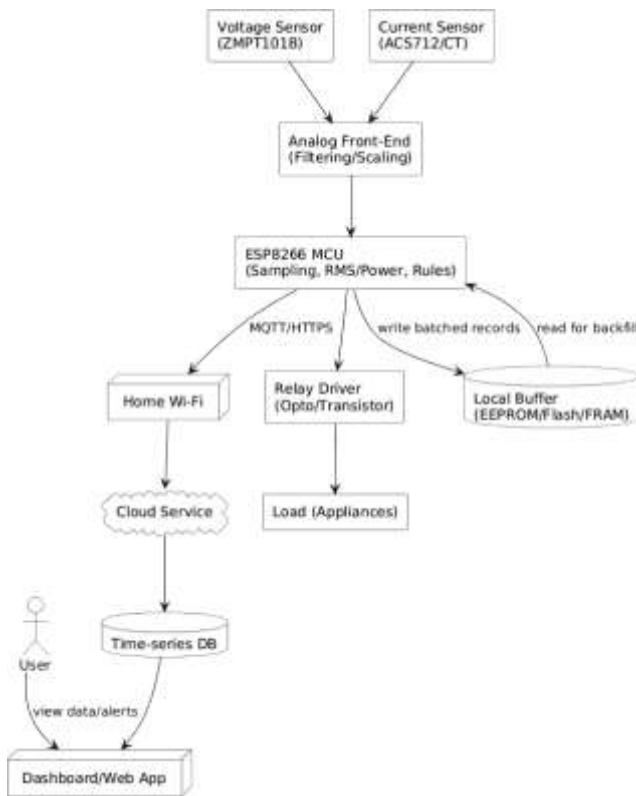


Fig. 1 System architecture and data flow

## IV. HARDWARE DESIGN

### A. Sensing and Isolation

- I. Voltage sensing: ZMPT101B transformer-based module (preferred for isolation and common-mode rejection).
- II. Current sensing: ACS712 Hall-effect module for compact AC measurement; optionally a CT for higher accuracy and isolation.
- III. Analog conditioning: anti-alias RC filters; scaling to ADC input range; attention to phase shift and temperature drift.

### B. Microcontroller and Power

- I. Controller: NodeMCU ESP8266 for integrated Wi-Fi and adequate processing for mains-synchronous sampling.

- II. Power supply: isolated SMPS module feeding 5 V; local regulation to 3.3 V for MCU; filtering to reduce noise injection.

### C. Protection and Actuation

- I. Relay: electromechanical relay sized for anticipated load; flyback suppression; zero-cross switching (if using SSR).
- II. Driver: opto-isolated transistor stage to protect MCU.
- III. Fusing: primary-side fuse and MOV/TVS for surge suppression; clear creepage/clearance.

### D. Storage and Timekeeping

- I. Local storage: onboard EEPROM/Flash or external SPI FRAM for high endurance.
- II. RTC: optional battery-backed RTC for stable timestamps during outages.

### E. PCB and Enclosure Considerations

- I. Isolation slots and creepage distances on PCB; differential routing for sensor signals.
- II. Enclosure rated for mains; shrouded terminals; cable strain relief; airflow for thermal safety.

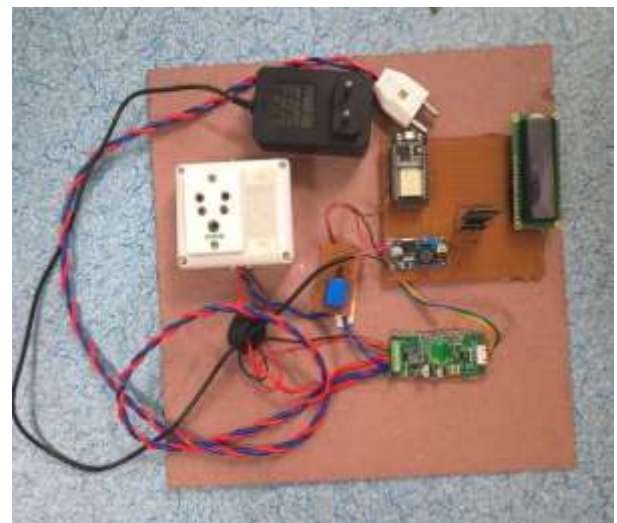


Fig. 2 Assembled prototype in enclosure

## V. FIRMWARE AND ALGORITHMS

### A. Sampling and Computation

- i. Sampling: acquire voltage and current at a fixed rate aligned to mains (e.g., 2–4 kHz), using an integer number of cycles for RMS.

- ii. RMS: compute RMS voltage and current over windowed samples; apply offset removal and calibration coefficients.
- iii. Active power and energy: compute average of instantaneous  $v \cdot i$  over the window; integrate over time for cumulative watt-hours.
- iv. Phase compensation: apply small phase shift or calibration factor to account for sensor-induced lag.

## B. Protection Logic

- i. Over/undervoltage thresholds with hysteresis.
- ii. Debounce: require N consecutive windows beyond threshold to assert a trip.
- iii. Relay control: zero-cross-aware actuation where possible; minimum off-time and cooldown to prevent chattering.
- iv. Event logging: record trip, restore, and duration with codes for diagnostics.

## C. Offline-First Storage

- i. Structure: circular buffer of fixed-size binary records (timestamp/seq, metrics, flags).
- ii. Wear management: page-level rotation; compaction; FRAM if heavy logging is expected.
- iii. Backfill: on reconnect, stream in chronological order; mark records ACKed by the server; discard only after confirmation.

## D. Connectivity and Sync

- i. Protocols: MQTT with QoS 1 or HTTPS with retry/backoff.
- ii. Idempotency: include monotonically increasing sequence numbers.
- iii. Timekeeping: RTC preferred; if absent, reconstruct wall-clock time from NTP on reconnect using stored deltas.

## E. Resilience

- i. Watchdog timer and brownout detection.
- ii. Partitioned tasks: acquisition, processing, storage, and networking run as separate, non-blocking loops or RTOS tasks.

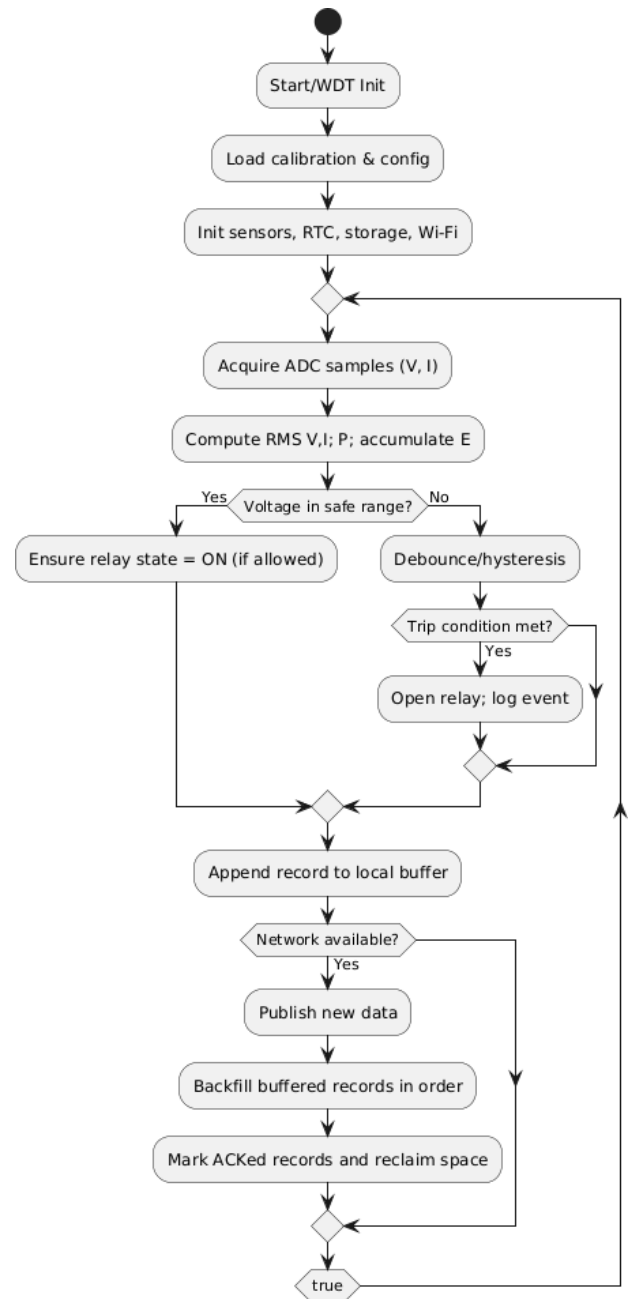


Fig. 3 Firmware pipeline and task separation

## VI. EXPERIMENTAL SETUP

### A. Testbed

- a. Supply: regulated AC source or mains with monitoring.
- b. Loads: resistive (lamps/heaters), inductive (motors), and SMPS loads.
- c. Induced events: over/undervoltage using variac or step-down transformer; Wi-Fi outages (router off), power cycles.

## B. Scenarios

- Steady-state accuracy at multiple load levels.
- Dynamic load changes and latency measurement.
- Protection trip tests with thresholds near limits.
- Extended outage with large buffered backlog and recovery.

## VII. RESULTS

We evaluated few scenarios and test results for the same are as follows,

TABLE I  
TEST RESULTS

| Scenarios | Description                     | Key Parameters    | Expected Outcomes     |
|-----------|---------------------------------|-------------------|-----------------------|
| S1        | Accuracy at 25/50/75/100 % load | V, I, P           | Errors within targets |
| S2        | Overvoltage trip                | V rises +10%      | Trip within 120 ms    |
| S3        | Undervoltage trip               | V drops -15%      | Trip within 143 ms    |
| S4        | Outage buffering                | Wi-Fi down 30 min | No data loss          |
| S5        | Backfill                        | Restore network   | Ordered sync          |

## VIII. CONCLUSION AND FUTURE WORK

This paper presented a low-cost, IoT-enabled smart energy meter that integrates real-time metrology, offline-first data handling, and automated protection. The prototype demonstrates stable measurement, deterministic protection behavior, and seamless data reconciliation after connectivity loss. Future work will focus on higher-accuracy metrology ICs, tamper detection, multi-phase support, prepaid/postpaid billing integration, stronger device security and OTA update mechanisms, and edge analytics for anomaly detection and demand response.

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