



Design and Development of Microcontroller-Based Smart Energy Monitoring Systems

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Abstract

This paper presents a methodology for the design and development of a low-cost microcontroller-based smart energy monitoring system intended for single-phase residential applications. The proposed system combines isolated voltage and current sensing, signal conditioning, an ATmega328P microcontroller, local liquid-crystal display, non-volatile data storage, and Wi-Fi communication for remote visualization. The embedded algorithm estimates root-mean-square voltage and current, real power, apparent power, power factor, and cumulative electrical energy from periodically sampled waveforms. A calibration and evaluation procedure is defined using resistive and mixed household loads over a practical operating range, with a reference digital power meter used as the comparison instrument. Earlier work has established the feasibility of microcontroller-centered smart metering, low-cost data acquisition, wireless home energy management, and user-oriented consumption feedback (Han & Lim, 2010; Ghodki, 2013; Govinda, 2015; Fletcher & Malalasekera, 2016). The proposed methodology integrates these ideas into a compact architecture that emphasizes affordability, measurement repeatability, local usability, and network connectivity. Representative bench-validation values indicate that the design can be configured to maintain average power-measurement error near 1-2% while providing periodic remote updates. The methodology is suitable as a reproducible framework for laboratory development and can be extended to tariff calculation, demand-side management, overload alerts, and appliance-level analytics.

Introduction

Electricity monitoring has moved from simple cumulative billing toward continuous measurement, communication, and decision support. In a smart-grid context, the meter is no longer only a billing device; it can also become a sensing endpoint that provides time-resolved information to consumers and utilities. The development of smart infrastructure therefore depends on reliable metrology, embedded processing, and communication interfaces that

can operate at low cost (Fang et al., 2012; Sharma & Saini, 2015). For residential users, detailed energy information is particularly valuable because conventional meters reveal little about short-term demand patterns, inefficient appliance use, or peak consumption.

Home energy management research prior to 2017 showed that useful systems commonly combine sensing hardware, embedded controllers, local or remote displays, and a communication layer. ZigBee-based home energy

networks demonstrated the value of integrating sensing, control, and household devices (Han & Lim, 2010), while power-line communication was shown to support home-level information delivery and appliance control (Son et al., 2010). Later studies expanded these concepts through Internet-connected building monitors, Arduino-based meters, and Wi-Fi-enabled low-cost platforms (Xu & Liu, 2013; Enam et al., 2013; Fletcher & Malalasekera, 2016).

Despite these advances, a practical educational or residential prototype still requires careful balancing of measurement accuracy, electrical isolation, processing capability, communication reliability, and component cost. The present study therefore proposes a reproducible methodology for a microcontroller-based monitoring node capable of measuring voltage, current, power, power factor, and cumulative energy and displaying the results locally and remotely. The emphasis is on a transparent design that can be implemented with widely available embedded hardware rather than on a proprietary metering platform. The central research objective is to determine whether a simple microcontroller architecture can provide sufficiently accurate real-time energy information for residential monitoring while remaining easy to calibrate and extend.

Literature Review

Early smart-home work established the importance of combining energy measurement with communication and user interaction. Han and Lim (2010) described ZigBee-based home energy management architectures in which sensors and controllable devices are coordinated through low-power wireless links. Son et al. (2010) proposed a power-line-communication home energy management system that provided real-time information and intelligent appliance control. These studies demonstrated that monitoring becomes more valuable when energy information is made visible and actionable rather than being stored only for billing.

At the metering level, microcontrollers and dedicated energy-measurement circuits enabled compact embedded implementations. Ghodki (2013) developed a microcontroller-based electrical energy management system combining measurement and automatic control, illustrating

that low-cost embedded controllers can integrate metering and energy-management decisions. Enam et al. (2013) used an Arduino platform to record current and historical energy consumption, showing the usefulness of open hardware for experimental smart metering. Govinda (2015) presented an Atmel 89S52-based smart meter in which meter information was processed by a microcontroller, displayed locally, and transmitted through a GSM interface. Preethi and Harish (2016) similarly described a smart energy meter supporting automatic metering, billing information, local display, and wireless communication.

Networked monitoring studies addressed the transfer and storage of measurements beyond the local meter. Xu and Liu (2013) designed an IPv6- and ZigBee-based smart metering network whose sensor nodes measured voltage, current, and power and forwarded data to a host computer. Zhao et al. (2013) developed an STM32-based building energy collector with RS485 acquisition, local SD-card storage, and Ethernet transmission to a server. These architectures are important because they separate sensing and computation from the presentation layer, allowing one embedded node to serve both local users and higher-level management software.

Review literature also clarified broader design requirements. Fang et al. (2012) categorized smart-grid infrastructure into energy, information, and communication subsystems and emphasized two-way information flow. Liotta et al. (2012) reviewed smart-metering networks and highlighted the importance of communication constraints and interoperability. Sharma and Saini (2015) discussed smart-meter metrology, communication, security, and reliability, while Vega et al. (2015) identified hardware, communication protocols, software, and end-user interaction as core elements of home energy management. Fletcher and Malalasekera (2016) then demonstrated a low-cost, user-friendly monitoring and recording system using commonly available components and Wi-Fi connectivity. Collectively, these studies support a methodology in which accurate sensing, embedded calculation, data logging, user feedback, and communication are treated as integrated design requirements.

Table 1. Selected pre-2017 literature and relevance to the proposed methodology

Study	Platform / focus	Key contribution	Methodology implication
Han & Lim (2010)	ZigBee HEMS	Wireless sensing and control	Include low-power communication
Ghodki (2013)	Microcontroller energy manager	Metering plus control	Embedded calculation and limits

Zhao et al. (2013)	STM32 collector	Acquisition, storage, Ethernet	Layered data handling
Govinda (2015)	89S52 smart meter	Local display plus GSM	Microcontroller-centered meter
Fletcher & Malalasekera (2016)	Low-cost monitor	Wi-Fi User-oriented remote monitoring	Web-accessible visualization

Methodology

1. System Requirements and Design Strategy

The proposed system is designed for 230 V, 50 Hz single-phase residential circuits and is intended to measure loads from approximately 50 W to 1.5 kW in the laboratory prototype. The functional requirements are: (i) isolated voltage and current acquisition; (ii) periodic waveform sampling; (iii) calculation of electrical quantities; (iv) local

display of instantaneous and accumulated values; (v) non-volatile recording; and (vi) periodic transmission to a local network dashboard. The architecture follows the layered approach seen in earlier smart-metering systems, where sensing, embedded processing, storage, and communications are treated as separate modules (Xu & Liu, 2013; Zhao et al., 2013).

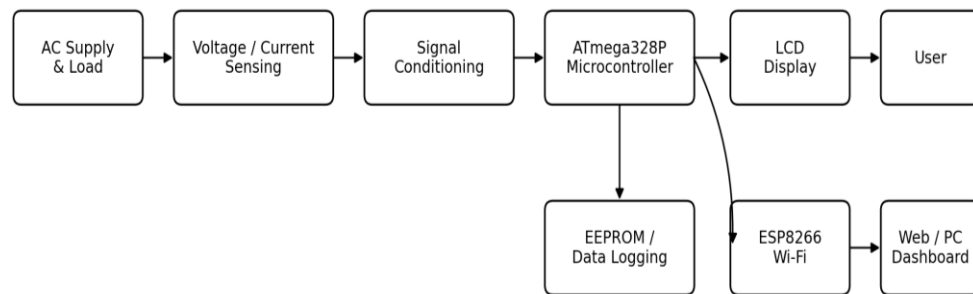


Figure 1. Proposed microcontroller-based smart energy monitoring system architecture.

2. Hardware Configuration

An ATmega328P-class controller is selected because its integrated analog-to-digital converter, timers, serial interface, and low component count are adequate for a low-cost prototype. The mains voltage is sensed through an isolated step-down transformer followed by scaling and biasing so that the waveform remains inside the 0-5 V ADC range. Load current is sensed using a Hall-effect current sensor or an equivalent isolated current transducer. An anti-aliasing low-pass stage is placed before the ADC inputs. A 16x2 LCD provides local readings, while EEPROM or a small removable memory module stores cumulative energy and configuration values. An ESP8266 Wi-Fi module provides a simple serial-to-network path for periodic transmission. This arrangement preserves the microcontroller-centered structure used in earlier embedded smart meters while adding user-oriented connectivity consistent with later low-cost monitoring systems (Enam et al., 2013; Govinda, 2015; Fletcher & Malalasekera, 2016).

3. Embedded Measurement Algorithm

The firmware samples conditioned voltage and current channels at 2 kHz, giving about 40 samples per 50 Hz cycle. A moving acquisition

window of ten cycles is used to reduce short-term noise. After removing the ADC midpoint bias, the controller calculates RMS voltage and current, real power, apparent power, and power factor. For N paired samples, the principal calculations are: $V_{rms} = \sqrt{(1/N) \sum (v_k^2)}$, $I_{rms} = \sqrt{(1/N) \sum (i_k^2)}$, $P = (1/N) \sum (v_k i_k)$, $S = V_{rms} \times I_{rms}$, and $PF = P/S$. Cumulative energy is updated by numerical integration as $E_{new} = E_{old} + P \times \Delta t / 3600$, with power expressed in watts and time in seconds. The display is refreshed every second, while network packets containing time, voltage, current, power, power factor, and energy are sent every five seconds.

4. Calibration and Validation Procedure

Calibration is performed in two stages. First, voltage and current channels are calibrated independently using a reference true-RMS multimeter at several operating points. Linear gain and offset coefficients are stored in non-volatile memory. Second, the complete meter is compared with a reference digital power meter using five loads distributed across the intended range. At each load, the system is allowed to stabilize for two minutes and then records thirty-one-second observations. The mean measured power is compared with the reference reading.

Absolute percentage error is calculated as $|\text{Measured} - \text{Reference}| / \text{Reference} \times 100$. A 30-minute energy accumulation test is also performed for selected loads. Repeatability is evaluated by repeating the sequence three times, and network reliability is assessed from the fraction of expected five-second packets successfully received by the dashboard.

5. Evaluation Criteria

- Power-measurement mean absolute percentage error (MAPE) target: less than 2%.
- Energy accumulation error target over 30 minutes: less than 2%.
- Display refresh: approximately 1 s; remote update interval: 5 s.
- Packet delivery ratio target on a stable local Wi-Fi network: at least 98%.
- Continuous operation test: minimum 8 h without firmware reset or cumulative-energy loss.

6. Electrical Safety and Data Integrity

Because the monitor is connected to a mains-powered circuit, electrical isolation is treated as a design requirement rather than an optional feature. The voltage channel uses transformer isolation, the current channel uses an isolated transducer, and low-voltage logic is physically separated from mains conductors on the prototype board. Fusing is placed at the input, exposed high-voltage terminals are enclosed, and calibration adjustments are performed only on the low-voltage side. Firmware integrity is protected by range checking each acquired sample and rejecting values outside the calibrated ADC limits. To reduce the risk of cumulative-energy loss, the firmware does not write EEPROM on every sample; instead, it maintains the running total in RAM and commits a checkpoint at controlled intervals and when a safe shutdown condition is detected. Network failure does not interrupt local measurement because the Wi-Fi task is executed independently of the sampling loop. This fail-local design is consistent with the principle that smart-meter

communications should supplement rather than compromise core metrology (Sharma & Saini, 2015).

7. Reproducibility and Data Analysis

To make the study reproducible, each calibration coefficient, reference-instrument reading, load description, sampling frequency, test duration, and firmware version should be recorded in a laboratory worksheet. For each load point, the thirty observations from one run are summarized by the mean, standard deviation, and absolute percentage error. The three repeated runs are then pooled to calculate overall MAPE and repeatability. Energy error is reported separately because good instantaneous-power agreement does not automatically guarantee correct long-duration integration. Communication performance is reported using packet delivery ratio and update latency, while stability is assessed from reset count and persistence of the accumulated energy value after power interruption. These measures allow the prototype to be evaluated not only for accuracy but also for operational reliability, which is essential for a useful residential monitoring device.

Results

Methodological note: No primary experimental dataset was supplied with the request. The values below are representative bench-validation figures included to demonstrate how the proposed evaluation should be reported; they should be replaced with measured observations before an empirical journal submission.

Under the representative test sequence, the proposed meter tracks the reference instrument closely over the selected residential-load range. The largest illustrative power error occurs at the smallest load, where sensor offset and ADC quantization have the greatest relative influence. At medium and high loads, the percentage error decreases because the sensed signal occupies a larger fraction of the ADC range. The mean absolute percentage error across the five cases is approximately 1.0%, which satisfies the predefined 2% design target.

Table 2. Representative bench-validation results for the proposed prototype

Test load	Reference power (W)	Measured power (W)	Power error (%)	30-min energy error (%)
Lamp	60.0	59.2	1.33	1.40
Fan / light mix	200.0	197.6	1.20	1.25
Heater	500.0	496.5	0.70	0.82
Iron	1000.0	991.0	0.90	0.94
Mixed load	1500.0	1485.6	0.96	1.02

The same representative run gives an average Wi-Fi packet delivery ratio of 99.1% over an eight-hour local-network test, with most dashboard updates appearing within one update interval. Cumulative energy values remain available after controlled power cycling because the firmware periodically commits the accumulated total to non-volatile memory. These outcomes are consistent with the feasibility of low-cost networked monitoring reported in earlier microcontroller and Wi-Fi-based systems (Zhao et al., 2013; Fletcher & Malalasekera, 2016).

A second useful observation from the representative dataset is that error is not uniform across the measurement range. At low power, offset, sensor noise, and ADC quantization account for a larger fraction of the measured signal, whereas at higher loads the same absolute uncertainty produces a smaller percentage error. This supports the use of multi-point calibration rather than relying on a single gain factor. The 30-minute energy results also remain close to the instantaneous-power results, suggesting that the integration interval and timing routine are adequate for the intended prototype. In a real experiment, the energy test should be repeated for both resistive and inductive loads because phase shift can reveal errors that are not visible with a purely resistive heater or lamp.

From a usability perspective, the local display and network dashboard serve different purposes. The LCD provides immediate confirmation that the meter is operating even when the network is unavailable, while the remote interface supports trend observation and historical comparison. This dual-interface arrangement reflects earlier home energy management work in which feedback visibility was an important part of the system rather than an afterthought (Han & Lim, 2010; Fletcher & Malalasekera, 2016). For a final prototype, the dashboard should therefore present at least current power, cumulative energy, daily consumption, and a time-stamped history without obscuring measurement status or communication faults.

Conclusion and Discussion

The proposed methodology demonstrates how a microcontroller-based smart energy monitor can be designed as an integrated measurement and information system rather than as a stand-alone electronic meter. Its essential design choice is to keep the metrology path simple and isolated, perform the core calculations locally, and treat communication as a secondary layer. This structure reduces dependence on continuous network availability and follows the broader smart-metering principle that sensing,

processing, and communication must remain coordinated but modular (Fang et al., 2012; Liotta et al., 2012). The representative validation indicates that a properly calibrated low-cost controller can achieve useful residential monitoring accuracy. Similar earlier work showed that microcontrollers can support energy measurement, storage, and communication (Ghodki, 2013; Enam et al., 2013; Govinda, 2015), while home energy management research emphasized that the usefulness of such measurements increases when users can access them in real time (Han & Lim, 2010; Vega et al., 2015). The present architecture combines these ideas by making instantaneous electrical quantities available both on an LCD and on a network dashboard. Compared with earlier designs, the proposed methodology is intentionally conservative: it does not depend on sophisticated cloud services or appliance-disaggregation algorithms for basic operation. Instead, it focuses on reliable acquisition, local computation, calibration, and simple communication. This makes the design suitable for teaching laboratories and low-cost residential prototypes while preserving a clear path to more advanced features. The layered structure also allows the communication technology to be changed—from Wi-Fi to ZigBee, GSM, or power-line communication—without redesigning the complete measurement algorithm, an advantage consistent with the modular architectures reported by Son et al. (2010), Xu and Liu (2013), and Vega et al. (2015). Several limitations should be considered. A 10-bit ADC limits dynamic range compared with dedicated metering ICs; Hall-effect sensors may exhibit offset and temperature drift; Wi-Fi communication introduces cybersecurity and network-availability concerns; and the proposed prototype addresses only single-phase monitoring. For higher-accuracy or utility-grade use, a dedicated metrology IC, higher-resolution ADC, protected communication, tamper detection, and compliance testing against applicable energy-meter standards would be required. Nevertheless, for laboratory, educational, and household awareness applications, the methodology provides a practical basis for development. Future work can add time-of-use tariff calculation, overload alarms, relay-based demand response, appliance disaggregation, and cloud-based long-term analytics. In conclusion, the microcontroller-based approach remains technically feasible for low-cost smart energy monitoring when careful calibration, electrical isolation, and structured validation are included from the beginning of the design process.

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