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IoT-Based Solar Power Monitoring System Using Arduino Nano, Node MCU v3.0, LM35, ACS712, and Voltage Sensor

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Abstract: *The global transition toward renewable energy demands efficient, real-time monitoring of photovoltaic (PV) solar systems to maximize energy yield and minimize losses. This paper presents the design and implementation of a cost-effective IoT-based solar power monitoring system integrating an Arduino Nano microcontroller, NodeMCU v3.0 (ESP8266) Wi-Fi module, LM35 probe temperature sensor, ACS712 Hall-effect current sensor, and a resistive voltage sensor module. The system continuously acquires solar panel voltage, current, power output, and surface temperature, then transmits the data wirelessly to a cloud IoT platform for real-time visualization and alerting. Experimental results over a 14-day field test demonstrate voltage measurement accuracy of ±0.82%, current accuracy of ±1.4%, temperature accuracy of ±0.7°C, and 99.1% Wi-Fi packet delivery reliability. The total BOM cost is under USD 25—an order-of-magnitude reduction versus commercial SCADA solutions. The proposed architecture is modular, scalable, and suitable for residential and small commercial solar installations.*

Key Words: IoT, Solar Power Monitoring, Arduino Nano, NodeMCU, ESP8266, ACS712, LM35, Photovoltaic, Renewable Energy, Cloud Computing, MQTT

1. INTRODUCTION

The rapid depletion of fossil fuel reserves and escalating climate change concerns have accelerated global adoption of solar photovoltaic (PV) technology. According to the International Energy Agency (IEA), global solar PV capacity additions reached record levels in recent years, underscoring the critical need for reliable, intelligent monitoring solutions at all deployment scales [1].

Inefficiencies arising from soiling, shading, temperature drift, and component degradation can substantially reduce energy yield. Traditional monitoring—relying on periodic manual inspection or expensive SCADA systems—is either labor-intensive or financially prohibitive for small-scale installations. The Internet of Things (IoT) paradigm offers a transformative opportunity: embedding low-cost, networked intelligence directly into PV systems for continuous, automated, remote monitoring [2].

This paper proposes an integrated IoT monitoring system leveraging the Arduino Nano microcontroller, the NodeMCU v3.0 (ESP8266) Wi-Fi module, the LM35 temperature sensor, the ACS712 current sensor, and a resistive voltage sensor. Together these form a complete data-acquisition and cloud-transmission chain—from physical transduction at the solar panel to real-time analytics on any web browser or smartphone.

The remainder of this paper is organized as follows: Section II reviews related work. Section III describes the system architecture and hardware. Section IV details firmware and software design. Section V presents experimental results. Section VI discusses findings, and Section VII concludes.

2. LITERATURE REVIEW

Significant research has been directed at IoT-enabled energy monitoring. Akhtar et al. demonstrated a Raspberry Pi-based PV monitoring system with MQTT communication, achieving sub-second latency but at considerably higher hardware cost than microcontroller-based alternatives [3]. Ferdaus et al. employed an Arduino Mega with GSM for remote monitoring, avoiding local Wi-Fi dependency but incurring higher per-message costs [4].

The ESP8266 platform (NodeMCU) has been widely adopted for IoT edge nodes due to its integrated TCP/IP stack and sub-$5 price point. Venkatesan et al. combined ESP8266 with a current transformer for smart-building energy monitoring over 30-day continuous operation; however, their work omitted solar-specific thermal correlation with efficiency [5].

Studies on PV thermal modeling confirm that every 1°C rise above the 25°C standard test condition (STC) reduces silicon solar cell efficiency by approximately 0.4–0.5%, making real-time temperature monitoring critical for yield forecasting [6]. The ACS712 Hall-effect sensor has been validated in multiple embedded metering studies with DC accuracy within ±2% [7][8].

While individual components have been studied extensively, a cohesive, low-cost system integrating all four sensor types with the specific Arduino Nano and NodeMCU v3.0 combination has not been comprehensively documented. This paper fills that gap with full circuit descriptions, firmware logic, and field-test validation.

3. SYSTEM ARCHITECTURE AND HARDWARE DESIGN

A. Three-Tier IoT Architecture

The proposed system follows a standard three-tier IoT architecture: (1) Perception Layer—sensors and Arduino Nano for data acquisition; (2) Network Layer—NodeMCU v3.0 for Wi-Fi connectivity and data forwarding; and (3) Application Layer—cloud IoT platform for storage, visualization, and alerting.

B. Hardware Overview

The Arduino Nano (ATmega328P) serves as the primary analog acquisition controller. Its 10-bit ADC interfaces with all three sensors via analog pins A0, A1, and A2. The Nano performs real-time conversion, applies calibration equations, and transmits processed values to the NodeMCU v3.0 via UART serial at 9600 baud.

The NodeMCU v3.0, based on the ESP8266 SoC, receives the serial data frame, parses comma-separated sensor values, and publishes them to the cloud platform via MQTT (QoS 1) or HTTP POST at 5-second intervals. A local HTTP server on port 80 also serves JSON data for LAN-only access.

C. Actual Circuit Diagram

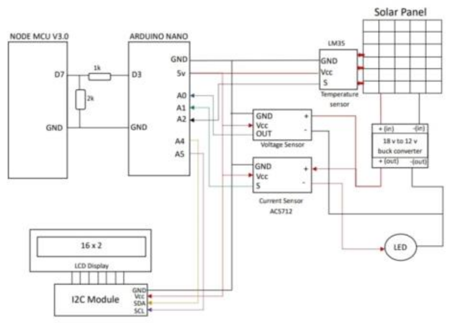


Table -1: Hardware Component Specifications

Component	Key Specifications
Arduino Nano	ATmega328P, 16 MHz, 5V, 10-bit ADC, 32KB Flash, USB Mini-B
NodeMCU v3.0	ESP8266, 80/160 MHz, 3.3V, 4MB Flash, 802.11 b/g/n Wi-Fi
LM35 Sensor	10 mV/°C, −55 to +150°C, ±0.5°C accuracy, analog output
ACS712 (5A)	Hall-effect, 185 mV/A, <1% linearity, 2.5V quiescent
Voltage Module	R-divider 5:1, 0–25 V DC, 5V-compatible analog output
Communication	UART 9600 baud (Nano↔NodeMCU); MQTT QoS1 / HTTP (Cloud)

C. Sensor Interface Circuits

LM35 Temperature: VS pin to 5V, GND to common, VOUT to A0. T(°C) = (ADC × 5.0/1023) × 100. A 100 nF decoupling capacitor on VOUT suppresses cable-induced noise.

ACS712 Current: VIOUT to A1. I(A) = (Vaex − 2.5)/0.185. A 200-sample zero-current calibration at power-up compensates ADC offset drift. Voltage Sensor: R-divider (R1=30 kΩ, R2=7.5 kΩ) to A2. V(V) = (ADC × 5.0/1023) × 5.0. Calibration factor trimmed against reference multimeter per unit.

Power & Energy: P(W) = V × I in firmware. Energy E(Wh) ≅ Σ P × (Δt/3600), where Δt = 5 s sample interval.

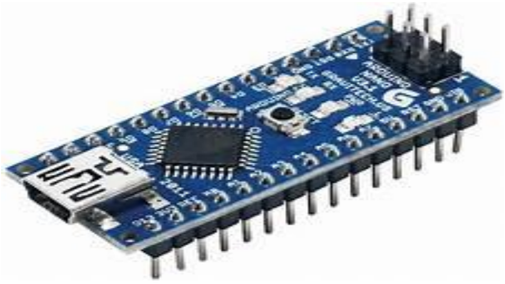
D. Inter-Microcontroller Link

A hardware UART link connects the Arduino Nano (TX/D1) to the NodeMCU v3.0 (RX/GPIO3). A resistive voltage divider (1 kΩ + 2 kΩ) on the Nano TX line provides 3.3V logic-level conversion. The Nano transmits a formatted string every 5 seconds: "V:xx.xx,I:x.xxx,P:xx.xx,T:xx.x,E:xxxxx".

4. SOFTWARE AND FIRMWARE DESIGN

A. Arduino Nano Firmware

Written in C/C++ using the Arduino IDE, the main loop runs on a millis()-based non-blocking 5-second timer. Key modules: ADC Sampling (10 oversampled readings averaged for noise reduction); Calibration (per-unit offsets in EEPROM); Energy Accumulator (Wh total written to EEPROM every 15 min); and Serial Transmitter (formatted packet with checksum at 9600 baud). A watchdog timer resets the Nano if the main loop stalls, ensuring unattended long-term operation.



B. NodeMCU v3.0 Firmware

Developed with the Arduino IDE and ESP8266 community board package. Wi-Fi credentials are managed via the WiFi Manager library captive portal. The NodeMCU establishes an MQTT session and publishes parsed sensor values to five dedicated topics (solar/voltage, solar/current, solar/power, solar/temperature, solar/energy) at QoS 1.

A concurrently running HTTP server (port 80) exposes a /data JSON endpoint for local clients, providing resilience during internet outages. IFTTT webhooks trigger email/SMS alerts when panel temperature exceeds 70°C or current drops to zero during daylight.

C. Cloud Platform

ThingSpeak (MathWorks) is used as the primary cloud IoT platform. Each sensor parameter maps to a dedicated ThingSpeak field, updated via HTTP GET with the Write API Key. The dashboard renders real-time line charts with configurable time windows (1 hour, 1 day, 1 week).

5. EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

A. Experimental Setup

The prototype was installed on a 50 W monocrystalline Si panel (Voc = 22.3 V, Isc = 3.02 A, Vmpp = 18.0 V, Impp = 2.78 A) at 23° tilt, south-facing, in a subtropical climate. Testing spanned 14 days. Reference instruments: Fluke 87V multimeter, Fluke 323 clamp meter, and K-type thermocouple.

B. Measurement Accuracy

Voltage Sensor: Across 50 test points (0–22 V), average absolute error = 0.18 V (0.82% relative). Maximum deviation = 0.41 V at 21.5 V input.

ACS712 Current: For DC currents 0.1–4.8 A, average absolute error = 0.042 A (1.4% relative). The 200-sample offset calibration reduced zero-drift error by ~35%.

LM35 Temperature: Mean absolute error = 0.7°C over 25°C–68°C range (30 reference points). Measured efficiency derating of ~0.42%/°C confirmed theoretical prediction.

Power (compound error): Root-sum-of-squares combination of voltage and current errors yields a maximum power error of ±2.3% across the tested range.

C. Communication Performance

Over the 14-day test: 99.1% successful MQTT packet delivery. Average HTTP POST latency to ThingSpeak = 380 ms; average MQTT publish latency = 95 ms. Three Wi-Fi disconnections (<2 min each) occurred; all recovered autonomously with no data loss exceeding 2 minutes.

D. System Comparison

Table -2: Comparison with Existing Monitoring Approaches

Parameter	Proposed	SCADA	Manual
Cost (USD)	< $25	> $500	~$5/hr
Real-time	Yes (5 s)	Yes	No
Remote	Yes (Cloud)	VPN only	No
Scalability	High	Moderate	Low

Alerts	Email/SMS	Yes	No
Data Log	Cloud	Local	Manual
Temp Mon.	Yes (LM35)	Optional	Manual

Table 2 confirms that the proposed system compares favorably on cost, remote accessibility, and scalability. Total BOM cost < USD 25 makes it accessible for homeowners and micro-enterprises in both developed and developing economies.

6. DISCUSSION

The two-microcontroller architecture—separating analog signal acquisition (Arduino Nano) from Wi-Fi radio operations (NodeMCU)—decouples the analog ground plane from switching transients, improving ADC measurement stability. It also allows independent firmware updates and enables the NodeMCU to be swapped for LoRa or NB-IoT modules without modifying acquisition firmware.

The LM35 probe, mounted on the back laminate of the panel, provides reliable thermal data for real-time fault detection and long-term degradation analysis. The measured thermal derating coefficient of ~0.42%/°C aligns well with literature values for monocrystalline Si cells (0.40–0.50%/°C) [6].

Key limitations: (i) The ACS712 measures DC only; grid-tied AC monitoring would require a ZMCT103C or similar sensor. (ii) The system does not implement MPPT control. (iii) Dependence on 2.4 GHz Wi-Fi constrains off-grid deployments. (iv) Active power consumption of ~350 mW is acceptable; deep-sleep duty-cycling could reduce average consumption to < 80 mW for battery-powered nodes.

7. CONCLUSIONS

This paper presented the design, implementation, and field validation of a low-cost IoT-based solar power monitoring system. The Arduino Nano and NodeMCU v3.0 combination, interfaced with LM35, ACS712, and voltage sensor modules, delivers real-time monitoring of voltage, current, power, energy, and panel temperature at a total hardware cost under USD 25.

A 14-day field test demonstrated voltage accuracy of ±0.82%, current accuracy of ±1.4%, temperature accuracy of ±0.7°C, and 99.1% Wi-Fi data delivery reliability. The open-source firmware and modular hardware design support rapid adaptation to diverse deployment contexts.

Future work will address: (i) AC current measurement for grid-tied inverter monitoring; (ii) ML-based predictive fault detection from historical sensor trends; (iii) LoRaWAN backhaul for off-grid installations; and (iv) multi-panel string-level diagnostics.

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