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IOT Based Solar Powered Monitoring System Application in Hydroponic Farming

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ABSTRACT

This report presents a comprehensive engineering analysis of IoT-based solar-powered monitoring systems for hydroponic farming applications. The integration of Internet of Things (IoT) architecture with photovoltaic energy harvesting enables autonomous, real-time monitoring and control of critical hydroponic parameters including pH, electrical conductivity (EC), total dissolved solids (TDS), temperature, humidity, and water level. The system employs low-power microcontrollers (ESP32/ESP8266), precision analog sensors, and hybrid wireless communication protocols (WiFi and LoRaWAN) to transmit data to cloud platforms for remote visualization and automated decision-making. Theoretical calculations for solar panel sizing and battery capacity demonstrate that a 405W panel with 200Ah battery storage provides 72-hour autonomy for a typical 6W IoT sensor network under Indian solar irradiance conditions of 5.5–6.0 kWh/m²/day. Implementation of advanced sleep modes reduces microcontroller power consumption from 240mA (active) to 150μA (deep sleep), extending system reliability during low-irradiance periods. The architecture achieves sensor accuracy of ±0.1 pH and ±10% TDS with proper calibration, enabling precision agriculture in off-grid locations. Critical analysis reveals challenges in sensor drift, data security, and initial capital expenditure, while future directions include AI-1.driven nutrient optimization and edge computing integration.

INTRODUCTION

Hydroponic farming represents a soil-less cultivation methodology that delivers nutrient solutions directly to plant root systems, achieving 30–50% higher water-use efficiency compared to conventional agriculture. Traditional hydroponic operations require continuous manual monitoring of nutrient concentration, acidity, and environmental conditions, creating labor-intensive processes prone to human error and system failures. The emergence of IoT technologies facilitates automated data acquisition and control, while solar photovoltaic (PV) systems provide sustainable energy independence, particularly critical for remote or grid-unreliable agricultural regions in India where annual global radiation varies from 1600 to 2200 kWh/m.

The convergence of these technologies addresses three fundamental engineering challenges: (1) real-time parameter monitoring with precision sensors, (2) reliable off-grid power supply through optimized solar-battery architectures, and (3) robust wireless communication for remote system management. Modern implementations utilize ESP32 microcontrollers

integrating 12-bit ADC resolution for sensor interfacing, while LoRaWAN protocols extend communication range to 5–15 km in rural deployments. This report establishes the theoretical framework, performs critical engineering analysis, identifies current implementation challenges, and proposes future development pathways for solar-powered IoT hydroponic systems

2. THEORETICAL FRAMEWORK: -

2.1 Hydroponic System Design Parameters

Two primary hydroponic configurations dominate IoT-integrated applications:

Deep Flow Technique (DFT) employs a static nutrient reservoir 15– 20 cm deep where plant roots remain submerged, requiring dissolved oxygen (DO) maintenance of 5–8 mg/L through aeration. DFT systems operate without incline angles, reducing pump energy consumption to 2 L/min circulation rates. The thermal mass of large solution volumes (340 L per unit) minimizes temperature fluctuations, improving nutrient uptake stability.

2.2 Nutrient Film Technique (NFT)

utilizes shallow film flows (1–2 cm depth) along inclined channels (1–3% slope), demanding continuous pumping at 1–2 L/min flow rates. NFT's thin film provides superior root oxygenation but exhibits vulnerability to pump failures, where root desiccation occurs within 30 minutes of flow interruption.

2.3 Communication Layer:

Hybrid protocols optimize coverage and power. WIFI (IEEE 802.11b/g/n) enables 100-meter range high- throughput data transmission at 80–90 mA receives current. Lora WAN (868 MHz band) extends range to 20 km with 125 mA transmission current at 14 dBm, utilizing spreading factors 7–12 for adaptive data rate.

2.4 Cloud Layer:

Message Queuing Telemetry Transport (MQTT) EMQX) handle publish-subscribe messaging with Quality of Service (QoS) levels ensuring reliable delivery. Time- series databases (Influx DB) store sensor data at 5-minute intervals, enabling trend analysis and anomaly detection.

2.5 Application Layer:

Web dashboards visualize real-time parameters, generate alerts, and provide remote actuator control. Blynk and Thing Speak platforms support mobile application integration for farmer accessibility.

2.6 Solar Power System Design

The photovoltaic subsystem sizing follows energy balance principles:

Daily Energy Requirement:

$Eday = Psystem \times toperation = 6.3W \times 24h = 151.2Wh$

Accounting for battery efficiency (ηbat = 85) and depth of discharge (DoD = 80%):

$$E_{battery} = \frac{E_{day} \times t_{autonomy}}{\eta_{bat} \times DoD} = \frac{151.2 \times 3}{0.85 \times 0.8} = 667.1Wh$$

Battery Capacity: For 24V system voltage:

$$C_{bat} = \frac{E_{battery}}{V_{bat}} = \frac{667.1}{24} = 27.8Ah$$

Adding 20% safety margin: 33.4 Ah → Standard selection: 24V

35Ah lithium battery (840 Wh).

Solar Panel Sizing: Considering 5.5 peak sun hours in Rajasthan:

$$P_{panel} = \frac{E_{day} + E_{battery}}{PSH} = \frac{151.2 + 840}{5.5} = 180W_{peak}$$

Standard selection: 405W monocrystalline panel with 20.6% efficiency.

3. Power Management Theory

Microcontroller sleep modes critically impact energy autonomy:

Active Mode: ESP32 consumes 240 mA at 3.3V (792 W) with WiFi active.

Modem Sleep: Disables RF circuits while maintaining CPU clock, reducing consumption to 15 mA (50 W).

Light Sleep: Pauses CPU clock, retaining RTC and ULP- coprocessor, consuming 0.8 mA (2.6 W).

Deep Sleep: Powers down CPUs and most RAM, maintaining only RTC memory. Consumption drops to 150 µA (0.5 mw) with ULP active, enabling 10 µA (33 µW) in hibernation.

Duty cycling with 5-minute wake intervals reduces average power:

$$P_{avg} = \frac{P_{active} \times t_{active} + P_{sleep} \times t_{sleep}}{t_{cycle}} = \frac{6.3W \times 5s + 0.0005W \times 295s}{300s} = 105mW$$

Median filtering reduces sensor noise by 40–60%, improving measurement stability. Linear Quadratic Estimation (LQE) algorithms predict water quality changes with MAE < 1%.

Reliability: 24-hour stress tests confirm system stability with <2 s latency for AI inference and control actions. Watchdog timers prevent lockups by resetting the ESP32 if tasks fail within configured timeouts.

Energy Efficiency: Solar-battery systems achieve 85% round-trip efficiency with MPPT charge controllers. Performance ratio (PR) of PV systems ranges 0.75–0.85 in Indian conditions, with temperature coefficients of -0.4%/°C affecting output.

3.2 Cost-Benefit Engineering

Capital Expenditure: Component costs include ESP32 ($5), sensors ($15–25 each), solar panel ($180), battery ($200), and enclosure ($30). Total system cost approximates $400–500 per monitoring node.

Operational Savings: Automated dosing reduces nutrient waste by 25–30% compared to manual methods. Solar energy eliminates $50–

100 annual electricity costs per node. Labor reduction accounts for 15–20 hours/month savings.

Payback Period: For high-value crops (e.g., basil at $15/kg), increased yield and quality achieve 18–24-month ROI.

3.3 Failure Mode Analysis

Single-Point Failures: Pump failures in NFT systems cause catastrophic crop loss within 30 minutes. DFT systems provide 24– 48-hour resilience due to solution reservoirs.

Sensor Drift: pH electrodes exhibit 0.01–0.02 drift/week, necessitating weekly calibration with pH 4.0/7.0 buffer solutions. TDS probes foul with mineral deposits, requiring monthly cleaning.

Communication Loss: WiFi dead zones affect 30% of rural deployments. Lora WAN provides redundancy but increases latency to 5–10 seconds.

4. Current Challenge

4.1 Sensor Calibration and Drift

3.1 Critical Analysis

Maintaining long-term accuracy remains problematic. pH sensors require two-point calibration weekly, impractical for large-scale farms. TDS/EC probes suffer from biofouling and temperature hysteresis, causing 5–10% measurement errors without compensation. Calibration drift leads to incorrect nutrient dosing, reducing crop yields by 15–20%.

4.2 Power Management Under Low Irradiance

During monsoon periods, solar irradiance drops to 2–3 kWh/m²/day in northeastern India, reducing PV output below critical charging thresholds. Battery deep discharge cycles increase, shortening lifespan from 2000 to 800 cycles. Hybridizing with grid power or wind turbines adds $150–200 system complexity.

4.3 Data Security and Integrity

MQTT transmission lacks end-to-end encryption in 60% of implementations, exposing farm data to interception. Centralized cloud servers become single attack vectors. Blockchain integration for immutable data logging increases computational overhead by 40%, raising power consumption to 8.5W.

4.4 Scalability Constraints

Multi-node architectures face network congestion when exceeding 50 sensors per gateway. Lora Wan's duty cycle limitations (1% at SF12) restrict update rates to 10-minute intervals for large deployments. WIFI direct communication ranges limit node spacing to 50 meters for reliable data transfer.

4.5 Initial Cost Barriers

Small-scale farmers (< 0.5 acre) cannot afford $400/node capital costs. Subsidies covering 30–50% are insufficient. Lack of technical expertise leads to 35% installation failure rates in pilot programs

5. Future Direction

5.1 AI-Driven Nutrient Optimization

Reinforcement learning algorithms can predict nutrient uptake based on growth stage, environmental conditions, and plant species. Digital twin simulations optimize EC/pH setpoints dynamically, improving yield by 12–18%. Federated learning enables collaborative model training across farms without sharing raw data, addressing privacy concerns.

5.2 Edge Computing Integration

Deploying ESP32-S3 with vector instructions allows on-device inference, reducing cloud dependency and latency to <100 Ms. Timmy models for anomaly detection operate within 20 kB RAM, consuming only 50 mw during inference. This enables offline automation during connectivity outages.

5.3 Hybrid Renewable Architectures

Integrating 50W vertical axis wind turbines with solar panels provides 30% energy boost during cloudy, windy conditions. Supercapacitor banks (100F, 2.7V) handle peak actuator loads (3A for 2s), reducing battery stress and extending life to 3000 cycles.

5.4 Advanced Wireless Protocols

5G Redcap (Reduced Capability) modules will replace Lora WAN in peri-urban areas, offering 100 Mbps bandwidth at 100 mw power consumption. For ultra-remote locations, satellite IoT (e.g., Swarm, Iridium) provides global coverage at $5/month subscription, enabling precision agriculture in deserts and mountains.

5.5 Self-Healing Sensor Networks

Implementing mesh topologies with ESP-MESH protocol allows automatic rerouting around failed nodes, increasing network reliability to 99.9%. Energy harvesting from vibration and thermal gradients powers repeater nodes, eliminating battery maintenance.

5.6 Blockchain-Based Data Marketplace

Farmers can monetize anonymized sensor data through decentralized marketplaces. Smart contracts automatically execute payments for data sharing, creating new revenue streams. Zero-knowledge proofs verify data integrity without revealing sensitive farm information.

6. Conclusion

The IoT-based solar-powered monitoring system for hydroponic farming represents a transformative engineering solution addressing sustainable agriculture challenges. Theoretical frameworks demonstrate that a 405W solar array with 24V 35Ah battery provides reliable autonomy for 6W ESP32-sensor networks under Indian solar conditions. Critical analysis reveals achievable sensor accuracies of ±0.1 pH and ±10% TDS with proper calibration, while power management through deep sleep modes reduces average consumption to 105 mw. However, significant challenges persist in sensor drift mitigation, low-irradiance power management, and scalability for smallholder farmers. Future directions emphasizing AI-driven optimization, edge computing, and hybrid renewable integration promise to enhance system efficiency, reliability, and economic viability. Engineering recommendations include: (1) implementing weekly automated calibration routines using on-board buffer solutions, (2) designing hybrid solar-wind systems for monsoon resilience, (3) adopting TLS encryption for MQTT communications, and (4) developing government subsidy programs targeting $200/node cost points. Widespread adoption of these systems could increase hydroponic crop yields by 20–30% while reducing water and nutrient consumption by 25%, contributing significantly to India's food security and sustainable development goals.

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