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IoT and AI-Driven Approaches for Energy Optimization in Off-Grid Solar Systems

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INTRODUCTION & AIM

The rapid expansion of off-grid solar photovoltaics necessitates robust IoT solutions to overcome intermittency and storage constraints, ensuring reliable autonomous operation.

- **The Challenge:** Autonomous solar microgrids face issues regarding intermittency, storage limitations, and efficiency management.
- **The Need:** Reliance on renewable sources (PV) requires intelligent strategies to ensure reliability without grid support.
- **The Solution:** Integration of Internet of Things (IoT) hardware with Artificial Intelligence (AI) for real-time monitoring and control.
- **Objective:** This study reviews IoT-based hardware platforms, communication protocols, and control strategies to identify optimal architectures for off-grid PV energy optimization.

METHODOLOGY

A structured literature review was conducted covering peer-reviewed journal articles, conference papers, and technical studies, most of them published between 2020 and 2025, with an emphasis on IoT-enabled PV microgrid implementations.

- **Key Focus Areas:**
  - **Hardware Platforms Analyzed:** Arduino, ESP32, NodeMCU, TTGO LoRa32, Raspberry Pi for sensing, monitoring, and edge analytics.
  - **Communication Protocols Evaluated:** Wi-Fi, ZigBee, LoRaWAN, NB-IoT, MQTT, and CoAP, focusing on energy efficiency, range, reliability, and scalability.
  - **AI & Optimization Techniques Reviewed:** ANN, LSTM, CNN-LSTM, RNN, PSO, GA, WOA-SA applied to PV forecasting, MPPT, DSM, and fault detection.
  - **Analysis of Experimental Frameworks:** IoT–SCADA integrations (Node-RED, Grafana, InfluxDB), hybrid edge–cloud systems, and PV monitoring testbeds.

RESULTS & DISCUSSION

The review shows that integrating IoT hardware, efficient communication protocols, and AI-based analytical models significantly enhances energy performance, autonomy, and operational robustness in off-grid PV microgrids.

Study	Platform	Application	Algorithm / Model	Performance Metric	Networking	Security
[1]	Arduino Uno	Low-cost PV monitoring	–	Voltage error < 1%	GPRS (SIM900) telemetry	Low
[2]	ESP32	Irradiance & power monitoring	Linear regression	Energy efficiency +10%	Wi-Fi + MQTT	Medium
[3]	NodeMCU	PV energy forecasting	Regression / ANN	98.9% accuracy	Wi-Fi + Cloud API	Low
[4]	Raspberry Pi 4B	Solar tracker	PID + IoT SCADA	22% energy yield improvement	LAN / Node-RED + Grafana	Medium
[5]	LoRa Node	Remote PV monitoring	–	99% transmission reliability	Private LoRaWAN	High
[6]	ESP32 + Cloud	Predictive control	RNN	−18% latency	Wi-Fi + MQTT + Cloud feedback	Medium
[7]	Raspberry Pi + NodeMCU Edge	Fault detection	Lightweight CNN	97% accuracy; shading drop 15.89→9.07 W; dust drop 15.89→5.97 W	Wi-Fi (local)	Medium
[8]	Digital Twin Platform	Agrivoltaic optimization	ML regression	22% yield increase	Local IoT sensor network	Low

Table 1 – Comparative Analysis of IoT Platforms and AI Algorithms in PV Systems

A. Hardware Trade-offs:
- **Low-Cost MCUs (Arduino):** Best for simple voltage monitoring but limited in processing power [1].
- **Efficient IoT (ESP32/NodeMCU):** Optimal balance between energy efficiency (+10%) and real-time connectivity via MQTT [2, 3].
- **Edge Computing (Raspberry Pi):** Enables complex tasks like Image Processing (CNN) for fault detection and local SCADA systems [4, 7].

B. Communication & Scalability:
- **LoRa Technology:** Proven superior for remote, wide-area monitoring with 99% transmission reliability [5].
- **Cloud Integration:** Hybrid architectures (Edge + Cloud) reduce latency by ~18% [6].

C. AI Implementation:
- Algorithms like PID and ML regression significantly improve energy yield (up to 22%) in solar tracking and agrivoltaics [4, 8].
- Lightweight CNNs on the edge can detect shading and dust faults instantly, preventing power drops (e.g., 15.89W → 5.97W drop mitigation) [7].

CONCLUSION

IoT integration transforms passive solar systems into active, intelligent microgrids capable of self-optimization and predictive maintenance, essential for decentralized energy transitions.

- **Efficiency:** IoT-based architectures provide a cost-effective pathway to significant energy yield improvements and reliability.
- **Architecture:** A hybrid approach combining Edge Intelligence (for immediate control) and Cloud Computing (for long-term analytics) offers the best performance.
- **Impact:** Adoption of predictive models (RNN, CNN) transforms maintenance from reactive to proactive, ensuring sustainability in decentralized grids.

FUTURE WORK

Advancing this field requires a focused evolution towards secure, ultra-low-power edge intelligence (TinyML) and standardized communication protocols for seamless interoperability.

- **Cybersecurity:** enhancing encryption for low-power IoT devices to protect grid data.
- **TinyML**: Developing ultra-lightweight models to run complex forecasting on basic microcontrollers (e.g., ESP32) without Cloud dependency.
- **Standardization:** Creating unified protocols for interoperability between different IoT vendors in solar microgrids.

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