Tropentag 2026
September 16-18, 2026
Conference on International Research on Food Security, Natural Resource Management and Rural Development
organised by the Universities of Göttingen and Kassel, Göttingen, Germany

Enhancing health monitoring of energy harvesting systems through edge analytics in off-grid smart irrigation systems

John Kimotho Nyambura[a], Dennis Mugambi Kaburu[a] and Stephen Kinyua Gitahi[b]

[a]Jomo Kenyatta University of Agriculture and Technology, Information Technology, Kenya
[b]Strathmore University, Nairobi, Kenya,

Abstract

Energy harvesting offers a sustainable solution by utilising ambient energy to efficiently capture, convert, and store power, particularly vital for off-grid devices that rely on limited battery power, susceptible to rapid depletion from computationally intensive applications demanding low latency and real-time responses. Ensuring the operational health of energy harvesting systems is critical; thus, this study evaluates an edge-computing architecture logic that leverages real-time sensor data for fault detection, early fault identification, and predictive maintenance to reduce downtime and enhance system reliability. The framework employs algorithms to optimise energy consumption, prolong operational lifespan, and ensure sustainability. Continuous analysis of energy input/output, environmental factors such as temperature and solar intensity, and energy trends at the edge enables detection of shading, faults, and failures. Results indicate that 90.5% of the energy harvested reflected stable operation, with shading accounting for 7%, faults 1%, and failures 1%. Additionally, the study identifies critical energy management points such as charge depletion and peak consumption hours, facilitating adaptive responses to changing energy patterns. A comparative analysis between standard edge analysis and integrated edge-predictive methods shows that the integrated system achieves an accuracy of 91.6%, compared to the edge analytics model with an accuracy of 86.2% effectively stabilising short-term fluctuations, generating fewer and more stable alerts, with a coefficient of determination R2 of 0.98. Overall, this approach enhances the scalability and sustainability of solar energy harvesting, particularly in off-grid scenarios, by providing timely fault detection, improving operational efficiency, and promoting sustainable energy practices that minimise waste and maximise energy use.

Keywords: Edge analytics, IoT-based monitoring, off-grid renewable energy systems, predictive maintenance, real-time analytics

*Corresponding author Email: johnkimotho6@gmail.com

Introduction

Off-grid renewable energy harvesting systems are a viable solution in the provision of power to remote areas. These systems are applicable in locations for which it is not economically or technically advantageous to extend the conventional grid, and thus are applicable for remote areas (Pathak & Khatod, 2024). Solar energy, due to its abundance and cost-effectiveness, has become a predominant source of power for off-grid applications such as smart irrigation, powering sensors, and autonomous devices. However, the efficiency and reliability of these systems are often compromised by environmental factors such as shading, dust accumulation, and equipment faults, which can lead to energy loss and system downtime (Muhammad & Hamidu, 2025). Traditional maintenance practices, including reactive and scheduled maintenance, are insufficient to address the dynamic and unpredictable nature of off-grid environments, often resulting in unplanned outages and increased operational costs. Moreover, the intermittency of solar energy generation requires real-time monitoring to optimize energy harvesting and ensure system stability (Rekula *et al.,* 2026). Recent advances in Internet of Things (IoT) technologies, sensors, and edge computing provide opportunities to enhance the operational health of energy harvesting systems through continuous, localized data analysis. Edge analytics involves processing sensor data at or near the data source, enabling immediate detection of anomalies such as shading, faults, or failures and facilitating predictive maintenance. This approach not only reduces latency and dependency on centralized data centres but also conserves communication bandwidth, which is often limited in remote settings (Rayhan, 2025). This study explores an edge-computing architecture tailored for off-grid smart irrigation systems that leverage solar energy harvesting. By analyzing real-time sensor data, the system aims to detect faults early, optimize energy use, and extend the operational lifespan of critical components, fostering more sustainable and resilient off-grid energy solutions.

Material and Methods

The proposed system architecture integrated solar energy harvesting components, environmental sensors, and edge computing devices to monitor and maintain system health in real time. The hardware setup included photovoltaic (PV) panels for energy collection, charge controllers, batteries for energy storage, and a network of sensors measuring variables such as solar irradiance, temperature, voltage, and current. These sensors continuously collected data crucial for assessing the performance and health of the energy harvesting system. The edge device employed a microcontroller-based processing unit capable of executing algorithms locally. Data acquisition follows a structured process where current, voltage, solar intensity, and temperature were sampled at defined intervals. This data was timestamped and stored temporarily on local memory before being processed through predictive analytics algorithms.

Results and Discussion

Fault, shading, and equipment failure anomaly analysis was performed to understand system performance health. Notifications were generated at timestamps where energy declined or shading events were detected, often caused by poor circuit connections or weather conditions. These alerts enabled technicians to perform immediate error correction, helping to prevent system downtime and ensuring optimal energy conversion processes. Despite these occasional issues, approximately 90.5% of the energy harvested data reflected stable, fault-free operation. This distribution is visually summarized in Figure 1, which shows that the majority of system states were normal, with only minor proportions attributed to faults (1%), shading (7%), and failures (1%). These findings underscore the vital importance of continuous correction and real-time

health monitoring in maintaining the reliability and efficiency of solar energy systems. The analysis aligns with the study in (Kappler *et al.*, 2024), which emphasizes the integration of health monitoring systems for real-time surveillance and proactive maintenance, an approach crucial for enhancing system longevity, performance, and degradation mitigation.

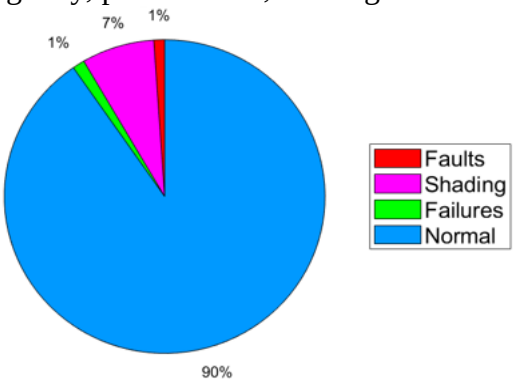


Figure 1: Solar monitoring event distribution

Figure 2 illustrates the off-grid solar energy system's daily offline periods and uptime, showing consistent operation with uptime frequently near 100%, yet revealing occasional sharp declines to 10-40% that signify intermittent disruptions. These fluctuations underscore the importance of edge analytics for real-time anomaly detection and timely maintenance, ensuring system reliability despite occasional interruptions.

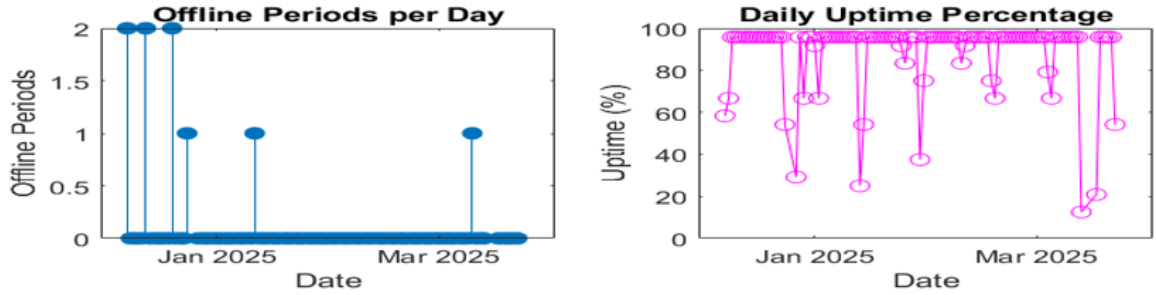


Figure 2: Off-grid solar energy system's daily offline and uptime

A comparative analysis between the baseline edge analytics model and the integrated edge-predictive model showed significant improvements. The integrated system achieved an accuracy of 91.6%, outperforming the standard model's 86.2%. Furthermore, the integrated approach demonstrated superior stabilization of short-term fluctuations, with fewer false positives and more stable alerts over time. The high coefficient of determination ($R^2 = 0.98$) indicates excellent predictive capability, affirming the system's robustness in energy forecasting and fault identification.

Conclusions and Outlook

This study demonstrates the effectiveness of an integrated edge analytics and predictive maintenance framework in enhancing the health monitoring of energy harvesting systems used in off-grid smart irrigation applications. By leveraging real-time sensor data and advanced algorithms, the system successfully detects shading, faults, and failures while optimizing energy consumption and extending system lifespan. The comparative analysis shows that the integrated approach achieves higher accuracy and stability, providing a more reliable basis for operational decision-making in resource-constrained environments. Future work will focus on incorporating

machine learning models for improved fault classification, expanding sensor networks for more comprehensive environmental monitoring, and exploring automation strategies for maintenance responses. Additionally, integrating renewable energy management with other IoT-enabled smart farming technologies presents opportunities for holistic agricultural optimization.

References

1. Kappler, T., Starosta, A. S., Schwarz, B., Munzke, N., & Hiller, M. (2024). Inclusion of Shading and Soiling With Physical and Data-Driven Algorithms for Solar Power Forecasting. *PV-Symposium Proceedings*, *1*. https://doi.org/10.52825/pv-symposium.v1i.1063
2. Muhammad, A. B., & Hamidu, M. (2025). Environmental Factors Affecting Solar Electric Output. *International Journal of Applied and Advanced Engineering Research*, *08*(5). https://doi.org/10.70382/mejaaer.v8i5.020
3. Pathak, D. P., & Khatod, D. K. (2024). A Review on Integrated Renewable Energy Systems for Off-Grid Rural Applications. In B.-M. Hodge & S. K. Prajapati (Eds.), *Proceedings from the International Conference on Hydro and Renewable Energy* (pp. 99–109). Springer Nature. https://doi.org/10.1007/978-981-99-6616-5_11
4. Rayhan, F. (2025). *AI-Powered Condition Monitoring for Solar Inverters Using Embedded Edge Devices* (2025080474). Preprints. https://doi.org/10.20944/preprints202508.0474.v1
5. Rekula, A., Nasam, V., & Sai, M. V. (2026). Digital Twin-Based Predictive Maintenance of Renewable Power Generation Systems. *2026 7th International Conference On Computational Vision and Bio Inspired Computing (ICCVBIC)*, 1905–1911. https://doi.org/10.1109/ICCVBIC71195.2026.11688661