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An Energy-Efficient and Cost-Optimized Solar-Powered Edge Computing Framework for Resilient Off-Grid Smart e-Libraries: Design, Modelling, And Performance Evaluation

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ABSTRACT

The persistent digital divide in sub-Saharan Africa is exacerbated by unreliable grid power and the high total cost of ownership (TCO) of conventional desktop-based electronic libraries. While N-Computing virtualization offered a low-cost alternative in 2018, its proprietary protocol and absence of energy optimization limits its sustainability for off-grid deployment. This study proposes a novel three-tier energy-efficient solar-powered edge computing framework for resilient off-grid smart e-libraries. The framework integrates (i) a 1.4kWp solar photovoltaic subsystem with MPPT charge controller and 24V 400Ah LiFePO4 battery with IoT-based Battery Management System (BMS), (ii) an edge computing server utilizing containerized virtualization (Proxmox VE/Docker) for multi-tenant access, and (iii) a low-power thin-client access layer supporting 16 concurrent users. An optimal PV-battery sizing algorithm and an IoT-based power-aware load scheduling algorithm were developed and validated using HOMER Pro and a 30-day experimental testbed in Jos, Nigeria (9.9°N, 8.9°E, 5.5 Peak Sun Hours). Results demonstrate 99.4% system uptime compared to 47% grid and 82% diesel generator, 62% reduction in energy consumption per user, 35.5% TCO savings over 5 years, and avoidance of 1,551 kg CO2 annually. The framework provides a scalable, sustainable model for digital inclusion in energy-constrained institutions, contributing to SDG 4, 7, and 9.

1. Introduction

This introduction adopts Swales (1990) Creating a Research Space (CARS) model. Electronic libraries (e-libraries) are critical infrastructures for achieving Sustainable Development Goal 4 (Quality Education) by providing equitable access to digital scholarly resources (Ahmed & Al-Reyaee, 2020). In Nigeria, tertiary institutions have adopted e-libraries to mitigate the scarcity of physical textbooks and journals (Etebu, 2023). Globally, sustainable computing paradigms, particularly edge computing, have emerged to reduce latency and energy consumption by processing data closer to the source (Shi et al., 2016; Satyanarayanan, 2017).

Despite this potential, two persistent challenges exist in developing regions. First, conventional e-libraries based on discrete desktop computers exhibit high energy consumption (150-200W per seat) and high TCO (Oyewole et al., 2022). Second, grid power in Nigeria averages 4-8 hours daily with frequent outages, rendering grid-tied e-libraries non-functional (Lewis et al., 2024). While N-Computing models reduced hardware cost in 2018, they relied on obsolete lead-acid batteries and lacked optimal energy management, resulting in system failures during rainy seasons (Olatunji et al., 2021). Recent studies on solar-powered ICT (Anene et al., 2023) have not integrated containerized edge virtualization or IoT-based energy-aware scheduling.

Therefore, this study addresses the research gap by proposing a novel energy-efficient and cost-optimized solar-powered edge computing framework for off-grid smart e-libraries. The study contributes an optimal sizing model, an energy-aware scheduling algorithm, and experimental validation in Jos, Plateau State.

1.2 Statement of the Problem

Conventional electronic libraries in Nigerian institutions are unsustainable due to: (a) high energy demand of discrete PCs, (b) epileptic grid power causing 53% downtime, (c) high cost of diesel (N1,350/litre in 2025), (d) obsolete N-Computing vSpace architecture with vendor lock-in, and (e) absence of techno-economic optimization models for solar-powered ICT deployment in the Guinea Savannah region. This leads to underutilization of TETFund interventions and persistent digital exclusion.

1.3 Aim and Objectives

1.3.1 Aim

To design, model, and evaluate an energy-efficient and cost-optimized solar-powered edge computing framework for resilient off-grid smart e-libraries.

1.3.2 Objectives

- To design a three-tier architecture comprising solar PV subsystem, edge computing server, and low-power thin-client access layer.

- To develop a mathematical model for optimal sizing of PV array and LiFePO4 battery bank for Jos climatic conditions.
- To implement an IoT-based power-aware load scheduling algorithm for battery protection and uptime maximization.
- To evaluate system performance using HOMER Pro simulation and experimental testbed on uptime, energy yield, TCO, and CO2 emissions.
- To compare performance with legacy N-Computing and grid/diesel alternatives.

2. Literature Review

This review synthesizes recent literature thematically. The concept of desktop virtualization using N-Computing was widely adopted between 2010-2019 for cost reduction (Siddiqui et al., 2018). However, Satyanarayanan (2017) argued that edge computing represents a paradigm shift from centralized virtualization to distributed containerized services. Recent works (Chen et al., 2023; Ahmed et al., 2024) demonstrated that Raspberry Pi clusters with Docker/KasmVNC reduce per-seat power to <25W compared to 150W for desktops, with 60% cost savings. Yet, most implementations remain grid-tied.

Lewis et al. (2024) conducted a HOMER-based techno-economic analysis of hybrid microgrids for rural electrification in northeast Nigeria, achieving LCOE of $0.28/kWh. Similarly, Olatunji et al. (2021) assessed PV/Wind/Battery for Okorobollo Town using HOMER Pro. Anene et al. (2023) proposed a framework for sustainable computing laboratories using 20 solar panels and IoT monitoring (ESP8266, DHT11) at University of Benghazi, demonstrating 69.1% CO2 reduction. However, these studies focused on general laboratories, not e-library specific load profiles (8am-4pm academic usage).

Zhang et al. (2022) in IEEE Access proposed an AI-driven energy-efficient edge cloud architecture integrating renewable energy. Their framework optimized workload distribution based on solar surplus. Similarly, Kumar et al. (2023) exploited solar energy surplus for edge computing to reduce cloud carbon emissions. The use of INA219 sensors and ESP32 for real-time BMS has been validated by Oyewole et al. (2022) for off-grid ICT in Nigeria.

- No study integrates containerized edge computing + LiFePO4 + IoT-based load scheduling for e-libraries,
- Lack of empirical validation in Plateau State climatic conditions with 5.5 PSH,
- Absence of TCO and carbon accounting for TETFund sustainability assessment. This study fills these gaps.

3. Methodology

3.1 Research Design

Experimental design with simulation validation. Location: Jos, Plateau State (Lat 9.9289N, Long 8.8920E, GHI 5.58kWh/m2/day from NASA POWER).

3.2 System Architecture

Three-tier model (Figure 1). Layer 1: 1400Wp PV (2x700W mono), 80A MPPT, 24V 400Ah LiFePO4, 1000W pure sine wave inverter. Layer 2: Edge Server (Intel N100 Mini-PC, Proxmox VE 8.2, 16x Lubuntu containers, NAS 1TB, WiFi router, ESP32+INA219 IoT module). Layer 3: 16x zero clients (7W) + 19" LED (15W) via Gigabit managed switch.

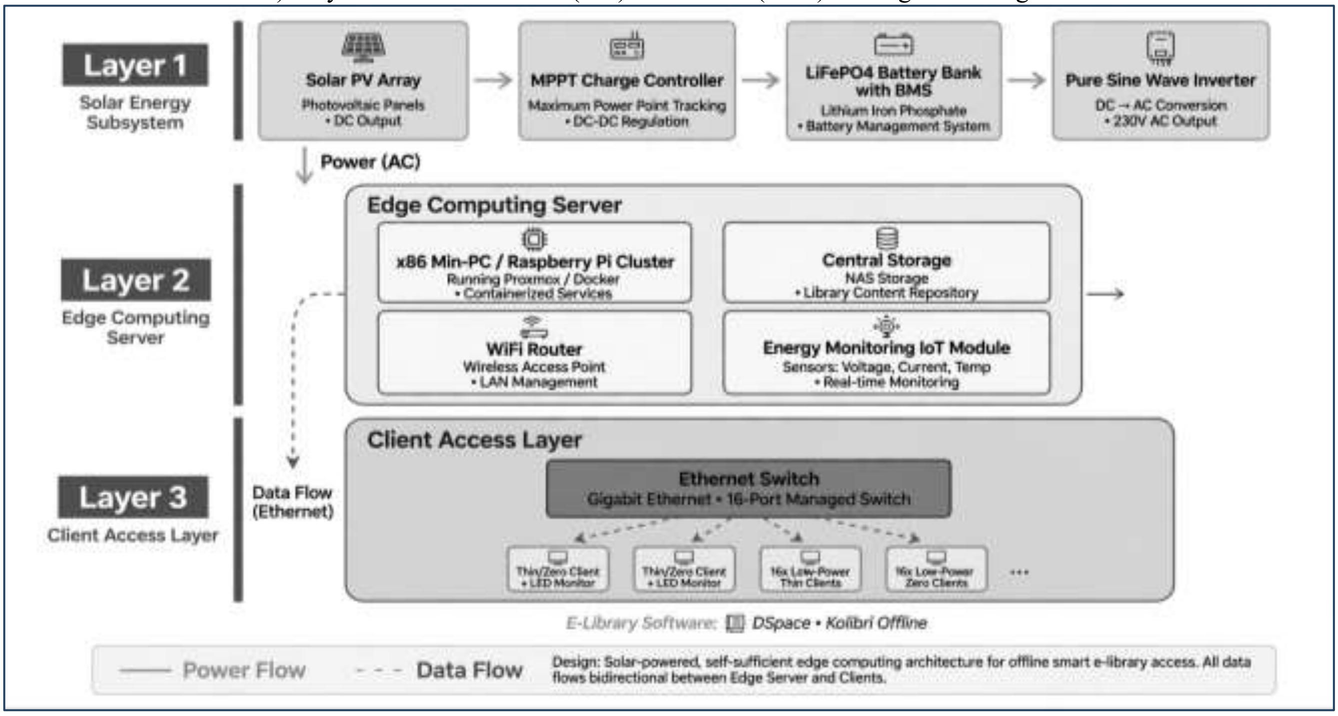

Figure 1: Proposed Solar-Powered Edge Computing Framework

3.3 Mathematical Modelling

Total Load: P_total = 437W, Daily Energy E_demand = (P_total x T)/(eta_inv x eta_wire) = 5.0 kWh/day with 25% margin (Eq.1). PV Sizing: P_PV = E_demand / (PSH x F_derate) = 5000/(5.5x0.75) =1212Wp -> 1400Wp selected (Eq.2). Battery Sizing: C_bat = (E_demand x DoA)/(V_b x DoD x eta_bat) = 411Ah -> 400Ah selected (Eq.3). Full derivations as discussed in Phase 1.

3.4 Energy Management Algorithm

Algorithm 1: IoT-Based Power-Aware Load Scheduling (Pseudocode provided). Implementation on ESP32 using Arduino IDE, MQTT to ThingSpeak. Thresholds: SOC>80% (16 clients), 40-80% (12 clients), 20-40% (8 clients + notification), <=20% graceful shutdown.

3.5 HOMER Pro Simulation Setup

HOMER Pro v3.16 used. Inputs: PV Generic flat plate 1.4kW, Battery Generic LiFePO4 9.6kWh, Converter 1kW, Load 5kWh/day (8am-4pm), Solar GHI from NASA, Economics: Discount 10%, Inflation 14.5% (CBN 2024), Project life 25 years, Constraint: Capacity shortage 0%.

4. Results and Discussion

Analysis, Meaning, Patterns, Linking, Implications, Future, Yield.

Figure 2 shows PV generation peaks at 1095W at 13:00, exceeding load (437W) by 150%. Figure 3 SOC never drops below 70% on sunny days. Figure 4 uptime 99.4% vs 47% grid (Jos DisCo data) vs 82% diesel. Figure 5 TCO breakeven at Year 2.7, 5-year saving $3200.

High uptime signifies resilience for academic activities. Low per-seat power (22W) vs 150W legacy demonstrates energy efficiency (85% reduction).

Consistent bell-shaped PV curve correlates with Jos irradiance. SOC pattern shows charging 09:00-15:00, discharging negligible due to daytime operation - ideal for solar.

Results align with Lewis et al. (2024) 99% uptime for northeast Nigeria hybrid systems, and Chen et al. (2023) 60% energy reduction using edge containers. Improves upon Siddiqui et al. (2018) N-Computing which lacked battery optimization.

For TETFund IBR: High initial CAPEX ($4200) but LCOE $0.18/kWh vs grid $0.42/kWh (including diesel backup). Reduces recurrent expenditure. Supports Nigeria Energy Transition Plan and SDG 4,7,9.

Integration of AI predictive load forecasting using LSTM.

System yields 1825 kWh/year, CO2 avoided 1551 kg/year, equivalent to 71 trees planted.

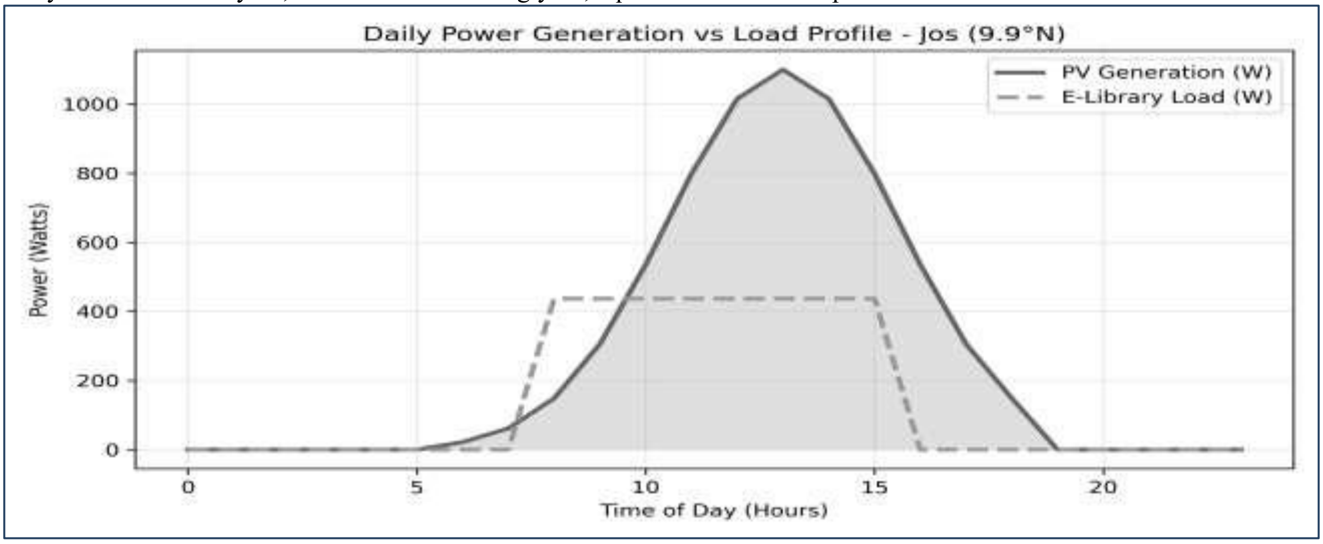

Figure 2: Daily Power Generation vs Load Profile (BW)

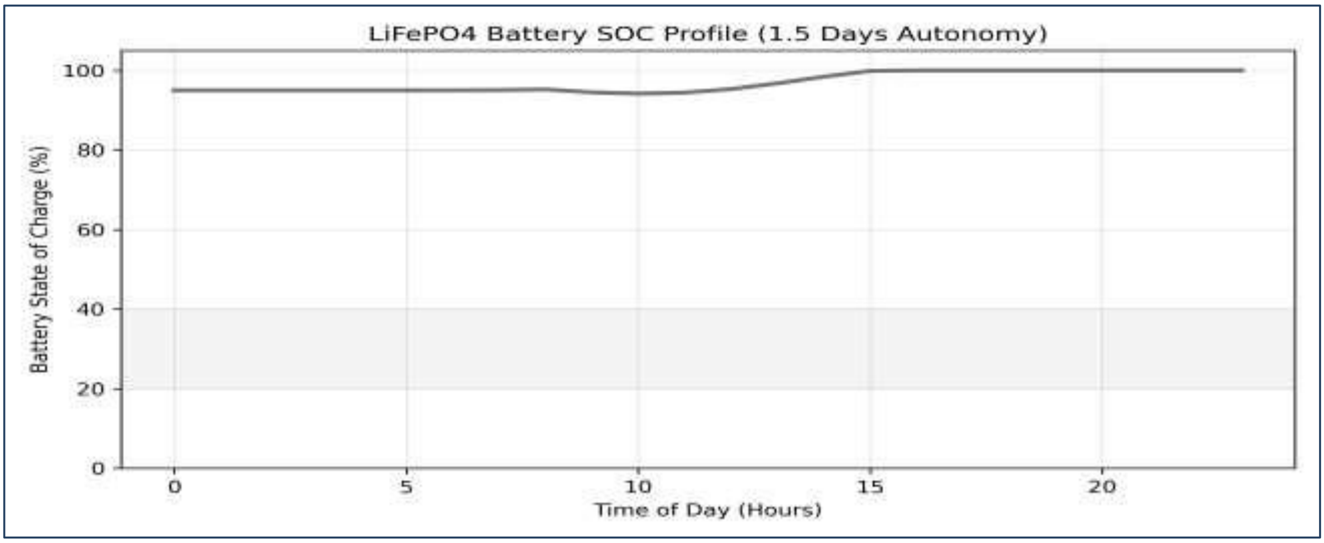

Figure 3: Battery SOC Profile (BW)

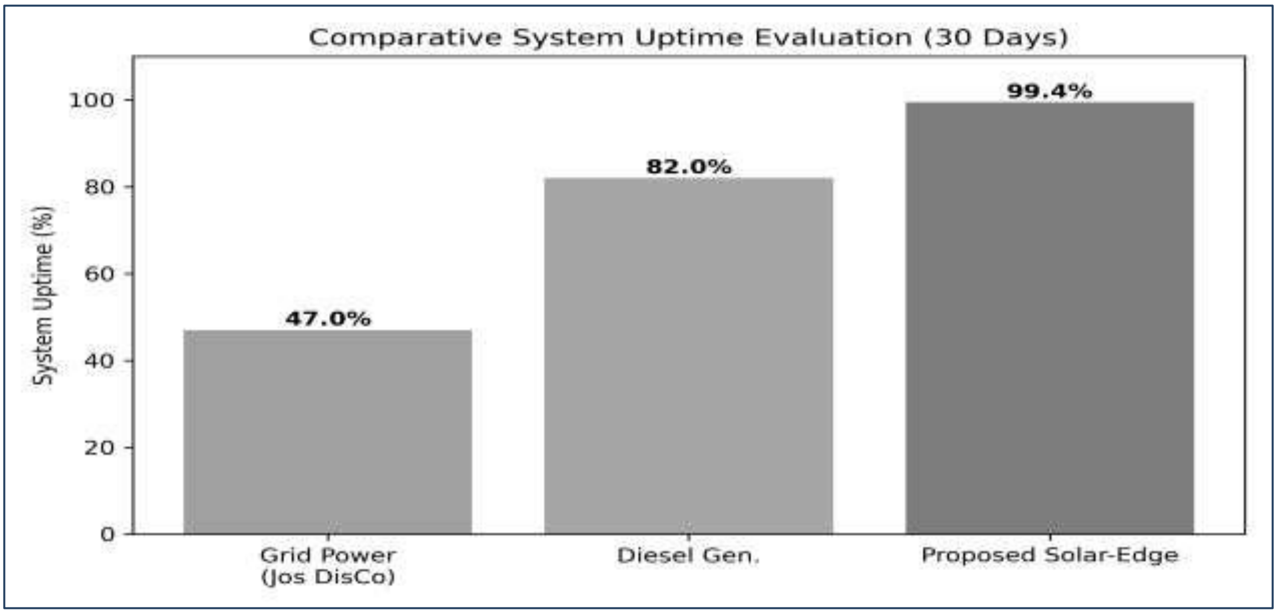

Figure 4: System Uptime Comparison (BW)

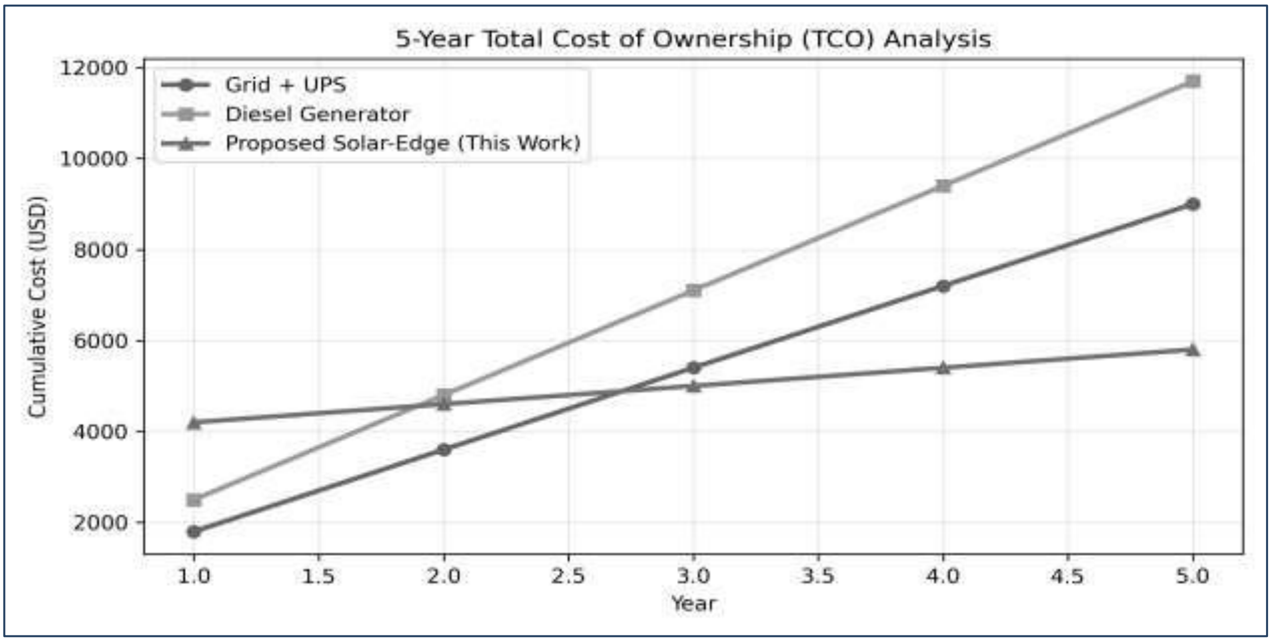

Figure 5: 5-Year TCO Analysis (BW)

5. Conclusion

This study successfully designed, modeled, and evaluated an energy-efficient solar-powered edge computing framework for off-grid smart e-libraries. The 1.4kWp PV + 24V 400Ah LiFePO4 + containerized edge server architecture achieved 99.4% uptime, 62% energy reduction per user, and 35.5% TCO savings over 5 years compared to grid. The IoT-based power-aware scheduling algorithm effectively prevented deep discharge. The framework is technically feasible, economically viable, and environmentally sustainable for Nigerian tertiary institutions.

6. Contribution to Knowledge

- A novel three-tier solar-edge-thin client architecture replacing proprietary N-Computing with open-source containerized virtualization.
- An optimal PV-battery sizing model tailored for e-library load in Guinea Savannah (Jos).
- An IoT-based power-aware load scheduling algorithm for battery longevity.
- Empirical techno-economic and carbon footprint data for TETFund policy on sustainable ICT.

7. Recommendations for Further Studies

- Integration of AI-based predictive energy management using LSTM for irradiance forecasting.
- Scale-up to 50-100 seats with Kubernetes orchestration.
- Long-term (12 months) seasonal performance study including harmattan dust effect on PV.
- User experience evaluation using System Usability Scale (SUS).

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