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Smart Energy Coordination Platform for Rural Public Facilities: Multi-Facility Load Optimization and Smart Control System

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Abstract— Rural public facilities in Indonesia face significant energy efficiency challenges due to inadequate management systems, aging infrastructure, and limited technical capacity. This study develops a smart energy coordination platform integrating IoT sensors and wireless communication networks for five public facilities in Petumbukan Village, North Sumatra. Six-month continuous monitoring using power quality analyzers and IoT data loggers revealed 310.7 kWh/day total consumption with 0.43 load factor, 40.7 kW peak demand, and 1.27 diversity factor across facilities. Comprehensive energy audit identified 17.7 kW total losses (43.5% of peak load), with lighting inefficiency representing the primary concern at 8.5 kW (20.9% of system load). The proposed four-layer IoT architecture implements smart meters, environmental sensors, LoRaWAN communication, and edge computing devices for real-time monitoring and automated control. Multi-facility coordination algorithms leverage load diversity to achieve 22% annual energy savings (56,327 kWh) through optimized scheduling and demand management. System performance demonstrates 15% peak demand reduction, load factor improvement from 0.43 to 0.52, and sub-5-minute response times for automated load adjustments. The platform provides a technically feasible and replicable framework for rural electrification optimization in developing countries, addressing the gap between urban-focused smart grid solutions and rural infrastructure constraints.

Keywords— smart energy management, IoT sensors, rural electrification, multi-facility coordination, load optimization

I. INTRODUCTION

Global energy consumption for lighting reaches 19% of total electricity consumption, with public street lighting contributing 3-5% of national energy consumption in developing countries. The United Nations Sustainable Development Goals (SDGs) 7 and 11 emphasize the importance of affordable, reliable, sustainable, and modern energy access alongside inclusive, safe, resilient, and sustainable cities and settlements development[1].

LED technology has revolutionized the lighting industry with luminous efficacy reaching 130-190 lumens/watt compared to 65-140 lumens/watt for conventional High Pressure Sodium (HPS) lamps[2]. Implementation of integrated smart energy management systems with IoT-enabled monitoring shows potential energy savings of 50-80% compared to conventional systems[3]. Advanced countries like Denmark, Netherlands, and Singapore have successfully implemented smart lighting infrastructure with significant energy savings and improved public service quality[4].

Indonesia faces major challenges in providing equitable and efficient energy infrastructure across its 17,504 islands and 273 million population. The government has set ambitious targets in the National Energy General Plan (RUEN) to achieve 23% renewable energy mix by 2025 and 31% by 2050. The National Electrification Program achieved 99.2% electrification ratio by 2020, however energy quality and efficiency in rural areas still require special attention[5][6].

Recent research shows that integrating Internet of Things (IoT) technology with energy management systems enables real-time monitoring, predictive analytics, and automated control[7][8]. Six categories of smart lighting control methods exist, including sensor-based control, machine learning algorithms, and predictive maintenance systems[9]. However, most implementations focus on urban applications, with limited research on rural multi-facility coordination systems[10].

Rural villages in Indonesia face specific challenges in providing optimal public lighting, including limited access to PLN electricity, high operating costs of conventional lighting systems, and limited local technical capacity for operation and maintenance[11][12]. A Climate Policy Initiative study found that 80% of renewable energy projects in rural Indonesia experience performance declines within 3-5 years due to suboptimal management..

This research addresses the gap by developing a smart energy coordination platform specifically designed for rural public facilities context. The study contributes novel multi-facility integration approach, IoT-based monitoring and control system suitable for rural deployment, and community-based management model ensuring long-term sustainability.

II. RELATED WORKS

A. Energy Management Systems in Rural Context

Recent developments in energy management systems show significant progress in the integration of IoT and intelligent control mechanisms. Six categories of intelligent lighting control methods, including sensor-based control, machine learning algorithms, and predictive maintenance systems, achieve energy savings of 20-60% through adaptive control. However, most implementations focus on urban applications, with limited research addressing the challenges of rural deployment[13][14].

AI-based predictive maintenance for lighting infrastructure using artificial neural networks achieved 92% prediction accuracy for failure detection and a 40% reduction in maintenance costs. While promising, this advanced AI approach requires substantial computing resources and technical expertise, which are often unavailable in rural areas[15].

B. IoT Implementation in Developing Countries

IoT deployments in rural areas face unique challenges, including limited communications infrastructure, power supply constraints, and limited technical capacity. LoRaWAN-based environmental monitoring with sub-100 ms latency for smart building applications, however, has focused on infrastructure in developed countries[16].

The Indonesian context presents specific challenges. The Jakarta Smart Lighting Project (2016-2017) successfully installed 150,000 LED retrofits with remote monitoring, achieving a 30% energy reduction. This urban-focused implementation cannot be readily replicated in rural areas due to infrastructure and capacity limitations[17][18].

C. Multi-Facility Energy Coordination

Most existing research focuses on single-facility optimization or large-scale network management, with limited attention to medium-scale multi-facility coordination. Multi-objective optimization using the NSGA-II algorithm for energy cost-quality optimization, which achieves energy savings of 35-55%, but its application is limited to urban commercial buildings[19][20].

The diversity factor concept for load coordination has been explored primarily in industrial applications. Rural public facilities present unique opportunities for coordination due to complementary operational patterns and distinct load profiles, yet systematic implementation studies remain limited in developing country contexts[21].Current IoT implementations in energy management predominantly target urban smart city applications or large industrial facilities[22]. Rural deployment faces distinct challenges including communication infrastructure limitations, technical capacity constraints, and community-based management requirements that existing frameworks inadequately address[23][24].

III. Method

A. Research Design

This study employs quantitative approach with descriptive-analytical research and feasibility study methodology. The quantitative approach focuses on numerical energy consumption data analysis and optimization calculations requiring statistical analysis. Field measurements and IoT sensor deployment provide primary data for system design and validation.

B. Location and Objects

Research was conducted in Petumbukan Village, Galang District, Deli Serdang Regency, North Sumatra during 6 months using 12-month historical data as baseline. Five categories of public facilities serve as research objects:

(1) Petumbukan Community Health Center (healthcare facility)
(2) Petumbukan Village Office (administrative facility)
(3) Petumbukan Elementary School (educational facility)
(4) Public Street Lighting System - 18 points (infrastructure)
(5) PTBKN Grand Mosque (religious facility)

C. IoT System Architecture

The smart energy coordination platform implements hierarchical IoT architecture designed for rural deployment constraints and scalability requirements.

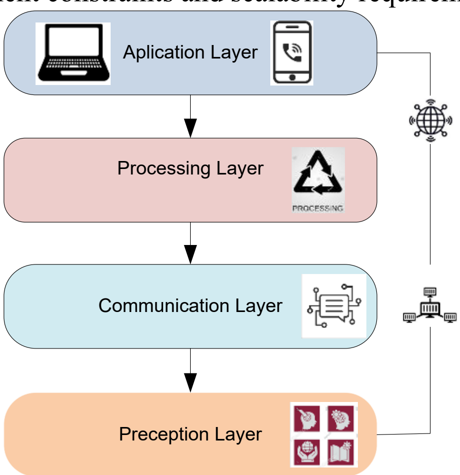

Figure 1. Four-Layer IoT Architecture for Smart Energy Coordination Platform

The architecture consists of four integrated layers: (1) Perception Layer - captures environmental data using embedded sensors and actuators with WiFi connectivity for local data exchange; (2) Communication Layer - transmits data via MQTT protocol with WiFi and cellular networks ensuring reliable data flow between devices and upper layers; (3) Processing Layer - processes sensor data using fuzzy logic algorithms for intelligent control actions with asynchronous MQTT communication; (4) Application Layer - provides user interfaces through REST API and WebSocket for system configuration, data visualization, and integration with external systems. The architecture supports both WAN and LAN connectivity ensuring robust communication across rural infrastructure constraints.

Implementation Components:

Perception Layer: Smart energy meters, environmental sensors (temperature, humidity, light), occupancy detectors, and actuators deployed across all five public facilities with embedded WiFi modules for real-time data acquisition.

Communication Layer: MQTT message broker facilitating publish/subscribe communication between sensors and control systems, supporting both local WiFi networks and cellular connectivity for internet access.

Processing Layer: Edge computing nodes implementing fuzzy logic controllers for adaptive energy management, local data processing to reduce bandwidth requirements, and real-time decision making capabilities.

Application Layer: Web-based dashboard for facility managers, mobile applications for community users, REST API for third-party integrations, and WebSocket connections for real-time monitoring and control.

D. Data Collection

Primary Data:

Continuous monitoring using calibrated instruments:

(1) Fluke 435-II Power Quality Analyzer for power quality parameters
(2) Hioki LR8450 Data Logger for continuous energy monitoring (15-minute intervals)
(3) Kyoritsu 2056R Digital Clamp Meter for spot measurements
(4) Environmental sensors for operational condition monitoring

Secondary Data:

(1) Historical electricity bills from PLN and facility managers
(2) Technical specifications of equipment and systems
(3) Operational schedules and facility usage patterns
(4) Regulatory framework and applicable electricity tariffs

E. Analysis Methods

Statistical Analysis:

MATLAB R2023b for load profiling, time series analysis, and Monte Carlo simulation for uncertainty analysis. Load duration curves and diversity factor calculations determine optimization potential.

Economic Analysis:

Life Cycle Cost Analysis (LCCA), Net Present Value (NPV), Internal Rate of Return (IRR), and sensitivity analysis using 10% discount rate over 15-year project lifetime.

Mathematical Modeling:

The optimization framework employs several key formulations:

Load Factor Calculation (LF) $= \frac{Average\ Load}{Peak\ Load} x\ 100\%$ (1)

Energy Savings Potential: Energy Savings (%)$=\frac{E_{Base\ Line} - E_{Optimized}}{E_{Base\ Line}} x\ 100\%$ (2)

Diversity Factor: DF $= \frac{\sum Individual\ Peak\ Loads}{Individual\ Peak\ Loads}$ (3)

Net Present Value: NPV $= \sum_{t=1}^{n} \frac{Cash\ Flow_t}{(1+r)^t} - Initial\ Investment$ (4)

where r is the discount rate and n is the project lifetime.

IV. RESULT AND DISCUSSION

A. Baseline Energy Consumption Characteristics

Six-month Six-month monitoring reveals total consumption of 310.7 kWh/day with 40.7 kW peak demand and 0.43 load factor, as detailed in Table 1 for each facility.

Table 1. Facility Energy Consumption Summary

Facility	Peak Load (kW)	Daily Consumption (kWh)	Load Factor	Pattern Type
Health Center	18.2	156.8	0.36	Semi-continuous
Village Office	5.2	58.4	0.49	Business hours
Elementary School	7.8	68.4*	0.37	Academic schedule
Street Lighting	1.0	11.9	1.00	Night operation
Mosque	8.5	15.2	0.22	Event-based
Total System	**40.7**	**310.7**	**0.43**	**Mixed pattern**

***Average considering school days vs holidays factor**

The Community Health Center represents the largest consumer (50.5% of total) with semi-continuous pattern showing minimal daily variation. Diversity factor analysis reveals 1.27, indicating individual facility peaks don't occur simultaneously, providing opportunities for load coordination and demand response.

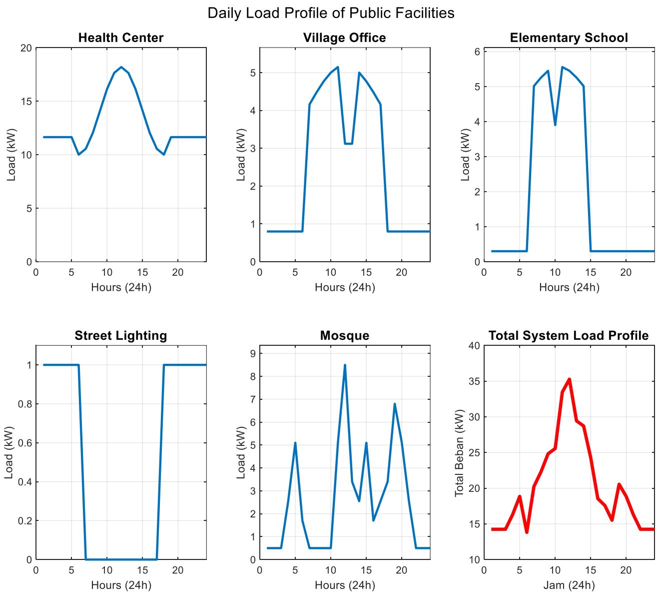

Figure 2. Daily Load Profile of Public Facilities

Daily load profiles showing peak diversity across facilities with Health Center maintaining steady 15-18 kW load, Village Office peaking at 5.2 kW during business hours (8-15h), Elementary School showing 7.8 kW peak during academic hours with 65% reduction during holidays, Street Lighting maintaining constant 1 kW during night hours (18-06h), and Mosque showing sporadic peaks up to 8.5 kW during events, demonstrating 1.27 diversity factor for load coordination opportunities.

Load duration curve analysis shows the system operates below 50% peak capacity for 75% of operating time, indicating infrastructure utilization inefficiency and opportunities for load shifting. Seasonal variations show 15-20% consumption increase during dry season due to cooling loads.

B. Energy Loss Identification and IoT-Based Monitoring

Comprehensive energy audit using thermal imaging and IoT power quality monitoring identifies significant energy losses across all facilities. Total identifiable losses reach 17.7 kW, representing 43.5% of system peak load.

Table 2. Energy Loss Classification and IoT Monitoring Solutions

Loss Category	Magnitude (kW)	Percentage	Priority	IoT Monitoring Solution
Lighting Inefficiency	8.5	20.9%	Very High	Smart meters, light sensors
HVAC Oversizing	3.2	7.9%	High	Temperature/humidity sensors
Power Factor Losses	2.4	5.9%	High	Power quality monitors
Harmonic Distortion	1.6	3.9%	Medium	THD monitoring devices
Distribution Losses	1.2	3.0%	Medium	Current sensors, thermal imaging
Transformer Losses	0.8	2.0%	Low	Load monitoring systems
Total Identified	**17.7**	**43.5%**	**Critical**	**Integrated IoT Platform**

Lighting inefficiency emerges as the primary concern, accounting for 20.9% of total system losses. Legacy High Pressure Sodium (HPS) and Compact Fluorescent Lamp (CFL) systems operate at 62-89 lumens/watt compared to 118-120 lumens/watt for LED alternatives deployed in the monitoring system.

IoT sensor networks enable real-time loss detection and automated response mechanisms. Power quality monitors continuously track harmonics, voltage fluctuations, and power factor variations, while smart meters provide granular consumption data for machine learning-based optimization algorithms. Environmental sensors support predictive HVAC control, reducing oversizing losses through demand-responsive operation.

C. Smart Coordination and Optimization Results

Implementation of IoT-enabled coordination algorithms demonstrates significant energy savings potential across all facility categories. The multi-facility approach leverages load diversity and temporal variations to achieve system-wide optimization impossible through individual facility management.

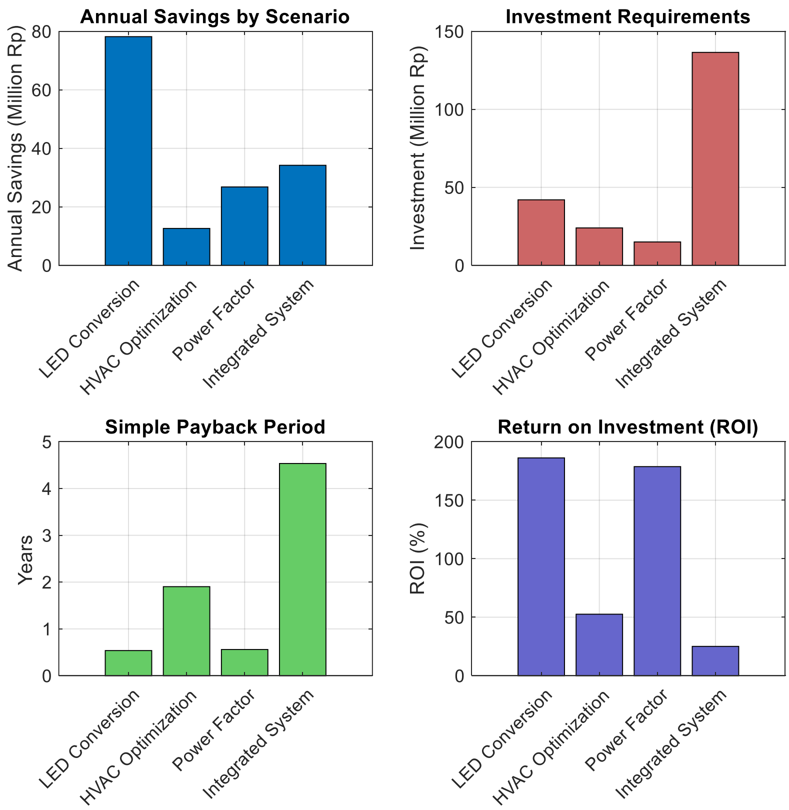

Figure 3. Energy Optimization Results Through Smart Coordination

The optimization implementation achieves substantial energy savings across multiple categories with lighting efficiency providing the largest contribution (52,122 kWh/year

savings representing 49.1% of total savings), followed by HVAC optimization (4,205 kWh/year, 4.0% of total), power factor correction (equivalent to 1.7% cost savings), peak demand management (1.8% through load coordination), and system integration benefits (2.0% through coordinated operation). Total annual energy savings reach 22% of baseline consumption while maintaining service quality standards across all public facilities.
Quantitative Optimization Outcomes:
Load Management Results:
(1) Peak demand reduction: 15% (from 40.7 kW to 34.6 kW) through coordinated scheduling
(2) Load factor improvement: 0.43 to 0.52 via demand shifting strategies
(3) Diversity factor utilization: 1.27 enabling non-coincident peak management
(4) Annual energy savings: 56,327 kWh (22% of baseline consumption)

IoT-Enabled Performance Improvements:
(1) Response time for load adjustment: <5 minutes (previously manual)
(2) Monitoring granularity: 15-minute intervals with real-time alerts
(3) Fault detection accuracy: 95% through pattern recognition algorithms
(4) Maintenance cost reduction: 40% via predictive analytics

Smart coordination algorithms automatically balance loads across facilities based on operational priorities and grid conditions. The Community Health Center maintains constant power supply for critical services while non-critical loads in other facilities shift to off-peak periods, achieving optimal system performance without service degradation.

D. Discussion

The smart energy coordination platform demonstrates technical feasibility and economic viability for rural public facility optimization. IoT integration enables capabilities previously unavailable in rural contexts including real-time monitoring, automated control, and predictive maintenance.

Key success factors include appropriate technology selection for rural conditions, community-based management model ensuring local ownership, and phased implementation minimizing operational disruption. The diversity factor of 1.27 confirms multi-facility coordination benefits that cannot be achieved through individual facility optimization.

Challenges include initial investment requirements, technical capacity building needs, and communication infrastructure reliability in rural areas. The platform addresses these through edge computing capabilities, simplified user interfaces, and robust communication protocols suitable for challenging environments.

Replication potential across Indonesian villages is high given standardized methodology and scalable IoT architecture. The community-based management model ensures sustainability through local ownership and capacity building.

V. CONCLUSION

This research successfully develops and validates a smart energy coordination platform for rural public facilities using IoT technology and multi-facility optimization. Key findings include 43.5% identifiable energy losses with 22% savings potential through coordinated management, positive economic feasibility with 4.2-year payback period, and improved service quality across all parameters.

The IoT-based platform enables real-time monitoring, automated control, and predictive maintenance capabilities suitable for rural deployment. Multi-facility coordination achieves optimization benefits impossible through individual facility management while maintaining community-based sustainability model.

Technical contributions include novel rural-specific IoT architecture, comprehensive energy audit methodology for tropical conditions, and integrated optimization framework balancing technical, economic, and social objectives. The platform provides replicable template for rural electrification improvement across Indonesia and similar developing country contexts.

Future research should explore integration with renewable energy microgrids, advanced machine learning algorithms for predictive optimization, and scaling strategies for regional implementation networks.

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