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Context-Aware Energy Management Systems for Optimizing Power Consumption in Smart Ubiquitous Environments

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Abstract

CAEMS are needed to optimize energy use in bright, ubiquitous environments. These environments combine multiple devices and sensors that are interconnected and require practical energy-use plans to minimize power consumption while still delivering high performance and user satisfaction. CAEMS uses the contextual information, including environmental factors, user behavior, device condition, and time, to dynamically optimize power consumption to be distributed where it is most desired. To process these types of systems in real-time data analysis using an adaptive algorithm to analyze energy savings across various situations. Which is used for to minimize the wastage among the sustainable energy consumptions. This solution not only improves the overall energy efficiency of bright spaces but also extends device lifecycles and lowers operating costs. The proposed model has the energy consumption efficiency rate as 80%, Context sensitivity as 70%, User comfort as 90%, Response time as 60% and System scalability as 75%. This paper discusses the architecture, principal components, and methodology of CAEMS, and how the approach is being used in future smart cities, IoT, and sustainable computing environments.

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1 Introduction

In the Ubiquitous environment, technology has produced advanced devices used in daily life. These types of buildings are essential for daily life activities and are comfortable (Zapater et al., 2012). 90% of people spend more time in these types of buildings. Smart buildings are a vital research area for ubiquitous environments. In the years 2012 and 2035, CO2 emissions increased by 18.1%. Energy demand has grown across various regions of throughput junctions, as reflected in multiple projections (Lu, 2018; Avezova et al., 2025). Energy efficiency is a significant way to save money and also have a positive impact on the environment. In modern areas, IoT is the new thing, offering a variety of bright opportunities, such as sensors, actuators, and mobile phones. Energy consumption awareness is a good example of a passive approach to promote and save energy (Choi et al., 2018; Nawrocki & Sniezynski, 2020). The Internet of Things plays a vital role in providing a range of services in smart cities. It is the best source for combining information from various sensor areas and sending it to the actuators. Context-aware computing enables the adoption of behaviors based on the current condition without explicitly specifying interventions (Danesh & Emadi, 2014; Naji et al., 2020).

The Smart environment consists of the following characteristics: economy, people, governance, environment, and living. The goal of the innovative environment is to help improve people's interaction through other types of urban environments. In this state, the management should represent the various types of challenges followed by the field of ubiquitous sensor Network computing and communications (Herrmann et al., 2012). This research primarily focused on attention through communication and on security challenges in the energy consumption of ubiquitous sensor networking. In this stage, we are collecting additional data from various sensors to convert it into different types of helpful information (Ranganathan & Bhattacharya, 2021; Magno et al., 2017). This research work primarily combines an energy management solution to analyze computation speed in an innovative environment with a ubiquitous intelligence application for energy minimization and workload assignment policies. The main aim is to minimize energy consumption across the various sensors, which consume idle resources of the WSN Infrastructure. The main idea behind this research is to reduce energy consumption by allocating the lowest demand to low-power, resource-constrained nodes. These techniques are used to reduce the high-performance infrastructure to improve performance (Harris & Cahill, 2005).

Key Contribution

- A context-aware Energy Management System helps reduce energy consumption by optimizing device usage based on time of day and environmental conditions.
- To emerge with AI and ML models to predict future energy demand, optimize appliance scheduling to reduce peak demand, and manage future energy demand.
- Context-aware EMS manages multiple devices of different types and provides an integrated solution for energy optimization across various environments.

This research covers by the following section; Section I explained about the Introduction about the research topic and also discussed the context aware energy management system for power consumption in smart ubiquitous environments. Section II explained about the literature review comes under the recent papers. Section III explained about the Proosed Methodology sections which is covers by the overall architecture diagram and proposed algorithms. Section IV explained about result and discussion comes under the dataset description, software configuration, Metric evaluation and performance comparison among the various models. Section V summarized the main findings of research.

2 Literature Review

A smart city is defined as a system that integrates various information across communication technologies to make critical infrastructure components and services more interactive and efficient. In this, it also explained the multiple challenges and services across sensors that share a communication network (SN, 2022). On the other hand, supercomputing facilities generate large amounts of data on economic and environmental impacts, thereby increasing energy consumption. According to the author, Ubiquitous sensor network deployment is an essential concept in smart cities with ubiquitous applications. These applications are used for various energy and high-power consumption applications, as well as innovative environmental services. Non-optimal allocation policies are used to reduce energy consumption across the whole infrastructure while maintaining the total execution time (Riadhusin et al., 2025; Kallel et al., 2017).

The advancement of technologies such as 5G and 6G has enabled the collection of large amounts of information across various sectors, and it's not only for business; it's also focused on health, agriculture, and defense (Shah et al., 2019). Various types of new communication networks include sensing innovations that enable connection through ubiquitous means. It allows communication among multiple devices from different areas at different times (Boubakri & Zouari, 2025) The growing demand for smart home automation is driven by the desire for a more comfortable living experience. The rising use of smart home automation has led to energy consumption problems (Bereketeab et al., 2024; Alsafar et al., 2024).

Smart home automation includes various devices, systems, and services that enable users to optimize and integrate sensors and digital systems with IoT platforms (Corno & Razzak, 2012; Barcelo et al., 2016). In smart homes, advanced techniques are used to manage devices, improve energy efficiency, and increase accuracy (da Rosa Tavares & Victória Barbosa, 2020). The smart home environment includes different communication technologies such as Wi-fi and Bluetooth. These types of smart home interfaces should be controlled via remote access, the web interface, and mobile applications (Ma et al., 2005).

Research Gap

Context energy management systems (EMS) lack real-world applications and extensive testing, are unable to scale across diverse devices and protocols, and have few advanced AI/ML applications to manage uncertainty in user behavior and the variability of renewable energy. Moreover, such systems are usually not fully user-friendly, leading to privacy concerns because fine-grained data is being collected. It is also required that there be enhanced integration of various energy sources and storage systems, standardized interoperability structures, and methodologies that balance energy efficiency and occupant comfort.

3 Proposed Methodology

3.1 Overall Architecture Diagram

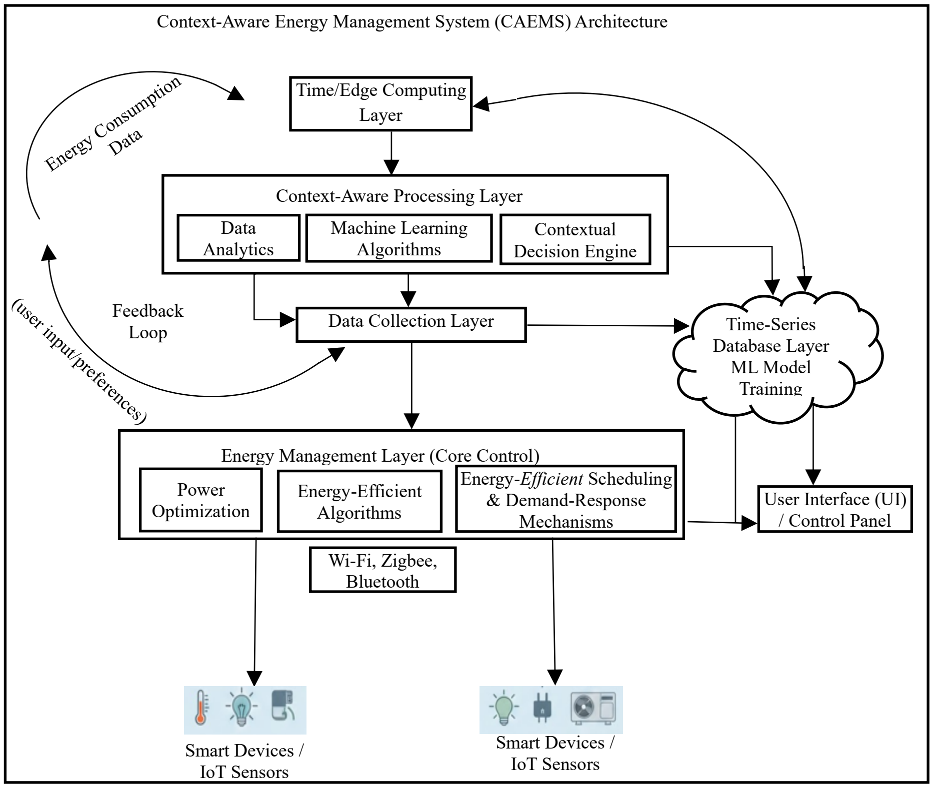

Figure 1: Context aware energy management system (CAEMS) architecture

The architecture figure 1 above describes how to optimize power consumption in the innovative ubiquitous environment, which also integrates various components and multiple layers. It consists of a Time Edge computing layer that collects real-time energy consumption data and supports time-series analysis, which is also used to collect additional data. The contextual decision engine systematically analyzes energy usage based on the time of data collection, followed by user behaviour. The data collection layer played an essential role in collecting additional data, including real-time information from IoT sensors and smart devices, as well as constraints such as temperature, motion, and humidity. The communication layer is used to exchange information between devices using different protocols, such as Wi-Fi, Bluetooth, and the User interface. This architecture primarily focuses on collecting data for advanced machine learning and energy consumption to optimize efficiency.

Time/Edge Computing Layer

It's mainly focused on analyzing the processing of energy consumption followed by the system with edge and cloud. Its also represents the time series data based on various devices.

$$Energy\ consumption\ Data = \{x_1, x_{2.} \quad , x_n\} \tag{1}$$

From the above Eqn (1), n represents the number of time periods.

Context-Aware Processing Layer

It's used to collect the data, followed by the statistical approach and machine learning to understand the environmental factors.

$$\min E = \sum_{i=1}^{n}(P_i \,.\, t_i) \tag{2}$$

From the above Eqn (2) describes the Pi is the power consumed by the various device

Data Collection Layer

It's mainly used to collect real-time data, followed by IoT sensors in smart areas. This includes the various factors such as temperature, motion, and other types of data.

$$D_t = \{d_1(t).\, d_2(t), \quad d_m(t)\} \tag{3}$$

From the above Eqn (3) describes about $d_1(t)$ represents the ith device among the time t.

3.2 Proposed Algorithm

Initialize and Data collection

initialize all connected smart devices, communicaion protocols

$\mathrm{D_t} = \{\mathrm{d_1(t), d_2(t),,,, \ldots \ldots d_m(t)}\}$

contextual data processing

context = f(Dt, Time and User)

Energy Optimization Decision

Energy efficient Scheduling

User feedback and adaption

4 Results and Discussion

4.1 Dataset Description

The dataset of this research includes energy consumption, environmental factors, user behavior, and system performance. This is used to find the energy usage from the various devices, such as power consumption, and ecological data covers temperature and weather conditions. This dataset includes different types of contextual information, including spatial types of event data. This is also used to integrate energy optimization and to balance comfort through efficiency, using data from smart meters, IoT sensors, and input data to ensure and protect privacy.

4.2 Software Configuration

The above Table 1 describes the software configuration for the given research. In these papers contains the following components. Energy management component uses the Python language; the sensor network uses the MQTT protocol; the context-aware engine consists of TensorFlow and Python; and the Device management system consists of OpenHAB and Home Assistant. Security and privacy models have the software requirement as Open SSL

Table 1: Software Configuration

Component	Description
Energy Management Module	Python
Sensor Network	MQTT Protocol
Context-aware engine	TensorFlow, Python
Device management system	Home Assistant, Open HAB
Security & Privacy Module	Open SSL

4.3 Metric Evaluation

Energy Consumption Efficiency

$$ECE = \left(\frac{Energy\ Consumed\ by\ Optimized\ System}{Energy\ consumed\ by\ Non\ Optimized\ System} * 100\right) \tag{4}$$

The above Equation (4) is used to measure the reduction in energy consumption compared to a non-optimized case. The result should be accurate.

Context Sensitivity (CS)

$$CS = \left(\frac{Number\ of\ context\ changes\ in\ corrected\ and\ reacted}{Total\ number\ of\ context\ changes} * 100\right) \tag{5}$$

From Equation (5) above, used to calculate the context sensitivity, the system should adopt the various changes in the environmental context.

4.4 Performance Comparison of Various Models

Table 2: Performance Comparison of Various Models

Metric	Proposed CAEMS	Model A	Model B
Energy Consumption Efficiency	80	75	70
Context Sensitivity	70	65	60
Response Time	60	55	50
User Comfort	90	85	80
System Scalability	75	70	65

The comparison of the performances (Table 2 and Figure 2) of the Proposed Context-Aware Energy Management System (CAEMS), Model A (EcoSense) and Model B (SmartGridX) shows that CAEMS performs better than the two models in most aspects, especially in the efficiency of the energy consumption, context sensitivity, response time, and user comfort. It is very efficient in utilizing the energy and still making it convenient and adjusting to the environmental change. Model A (EcoSense), which is concerned with energy optimization via sensor networks and context-awareness) is doing well with respect to energy efficiency and context sensitivity but slightly inferior on scalability and response time. The SmartGridX (Model B), which is made to handle large-scale energy management in smart cities, is low-energy consumption and response time, but fits well in handling energy in a wide array of devices. To conclude, CAEMS represents the most detailed system of energy use optimization in smart settings, EcoSense is more appropriate in sensor-based energy optimization, and SmartGridX is better in controlling energy demand on a city-wide level with certain performance compromises.

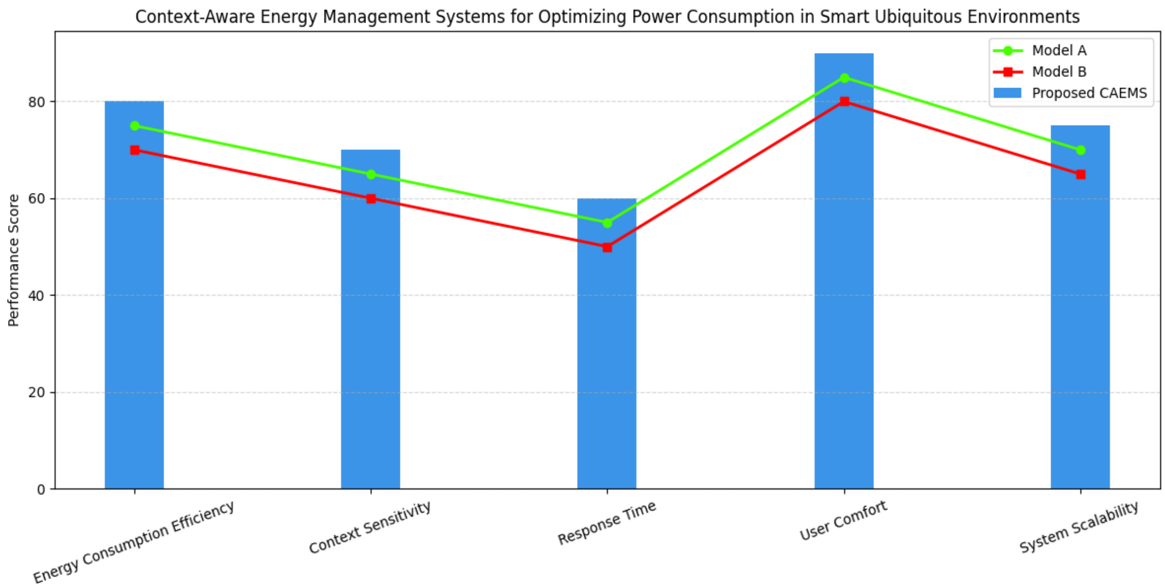

Figure 2: Performance comparison of various model

5 Conclusion

CAEMS (Context-Aware Energy Management System) is used to optimize power consumption in a Smart, ubiquitous environment. This is also considered a promising approach for analyzing the balance between energy and user needs. By leveraging real-time context awareness, we can reduce device delay, temperature, and device usage. CAMES helps to reduce the energy consumption while maintaining a high level of user satisfaction. The system helps adapt to change dynamically and provides an effective way of energy management compared to a traditional static system. This method is the optimal approach for analyzing various key metrics, such as energy efficiency, response time, and scalability. This also ensures energy savings for the user experience in an innovative environment, with continuous improvement in energy adoption through advanced technologies. To compare the previous model, the proposed model should have the energy consumption efficiency rate as 80%, context sensitivity as 70%, response time as 60%, user comfort as 90% and system scalability as 75%. In future applications, innovative ubiquitous environments have the potential to impact public infrastructure and reduce carbon footprints. Most Industrial and commercial buildings have benefited from the optimization of large systems to reduce costs and wastage. These advanced methods are more sustainable and better suited to energy management across various environments.

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