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Interfacing IoT Sensors with Library Energy Management Systems

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Abstract* - The integration of Internet of Things (IoT) technologies with Library Energy Management Systems (LEMS) presents a transformative approach to optimizing energy consumption within academic and public libraries. Libraries, as energy-intensive facilities, often face challenges in managing HVAC systems, lighting, and electronic resources efficiently. This study examines the integration of IoT-based environmental and occupancy sensors with existing LEMS to facilitate real-time monitoring, intelligent control, and data-driven decision-making. Incorporating temperature, humidity, motion, and light sensors into IoT systems enables libraries to make real-time adjustments, optimizing lighting and climate control systems based on actual environmental conditions and system usage. The study describes the system architecture and data integration methods for IoT devices, including communication protocols and platforms, with a focus on LEMS as the primary controller, utilizing MQTT and Zigbee. The pilot implementation in a university library surprisingly led to energy reduction and improved environmental comfort, as confirmed by a comparative analysis of energy consumption data before and after implementation. The system also promotes better predictive analytics and anomaly detection, which further enhances the operational and sustainability of library facilities. The research establishes key areas of concern, such as data security, system interoperability, and scalability of system components. The findings indicate the use of LEMS augmented with IoT systems to achieve the goals of green library projects and the intelligent, sustainable development agenda, specifying goals at the institutional level. This paper offers grounds for other policy recommendations on innovative energy management in the framework of knowledge institutions.

***Keywords* - IoT Sensor, Library Energy Management System (LEMS), Smart Libraries, Energy Optimization, Real-time Monitoring, HVAC Control, and Sustainability**

I. INTRODUCTION

The ongoing production of new technology and Internet of Things (IoT) has created a radical shift in the functioning of the energy systems in many industries, including education, and the area of public libraries (Ayesh, 2024). Libraries are traditionally viewed as information centres, but are increasingly becoming dynamic, technologically-oriented buildings with complicated energy requirements. The continuously increasing digitization of information and 24/7 access to resources substantially add to the energy requirement of HVAC systems, lighting, and computers in a library. Combining IoT sensors with Library Energy Management Systems (LEMS) provides an intelligent paradigm that can facilitate real-time monitoring of energy and optimal environmental conditions related to the occupancy and sustainability. Studies have shown that the introduction of the IoT-based systems can help reduce the energy management wastage by up to thirty percent in company buildings, through adaptive control and data-driven analytics (Khan et al., 2012). Therefore, the implementation of IoT into LEMS does not mean that it breaks new ground in energy technology, but it is a comprehensive solution to the challenges of energy efficiency and environmental sustainability on a global scale.

Moreover, smart libraries are also imagined as the place where data is considered one of the main priorities, and sensor networks can give useful information to managers and administrators (Menaka et al., 2022). The addition of sensors like temperature, motion, light, and humidity units also realizes automation of resource usage, and makes the user experience more comfortable. Although these measures improve user comfort, they also reduce operational costs. Interfacing with IoT-LEMS also enables libraries to be more adaptable and responsive to changing energy demands through advanced maintenance forecasting, security alert monitoring, system performance optimization, and dynamic energy management (Da Xu et al., 2014). Therefore, the significance of this integration extends beyond energy management to architectural space design for personalizing intelligent library services, which supports modernization initiatives in higher education and public services (Alam et al., 2012; (Sampedro & Wang, 2025; Atzori et al., 2010).

Key Contributions:

- The manuscript describes a Library Energy Management System that interfaces heterogeneous IoT sensors through a modular and scalable architecture, guaranteeing seamless data transmission and automated control.
- The proposed system was validated through a pilot implementation of energy-saving and improved environmental conditions in a university library, which empirically validated the LEMS system.
- The LEMS analytics framework, as described in this research, enables anomaly detection, usage forecasting, and operational optimization and extends the framework's capabilities toward strategic maintenance and long-term energy planning.

This research document is divided into five core sections. In Section I, we explain the fundamentals, relevance, and problem statement on interfacing IoT sensors with Library Energy Management Systems. In Section II, the literature review concentrates on the available literature on IoT applications in intelligent energy systems, particularly within the context of educational institutions. In Section III, we discuss the proposed approach, which consists of sensor integration, data processing models, and system architecture. In Section IV, we conduct a comprehensive examination of the analyzed results, including charts and tables, active benchmarks, and other performance metrics that demonstrate the system's efficiency, as illustrated in the document. Lastly, in Section V, we conclude the study by presenting a synthesis of the outcomes, along with specific conclusions and remarks regarding future research and practical work in the area of sustainable library management.

II. LITERATURE SURVEY

As a result of the global economic slowdown, significant developments have occurred in research related to the adoption of IoT. This includes the monitoring and management of energy utilization on a much broader scale, which can be implied as 'smart' energy systems. Leverage refers to the use of infrastructure, which includes, but is not limited to, sensor networks, automation, and cloud computing, regarding which these innovative environments are deployed efficiently (Siano, 2014). The concept of intelligent energy management using IoT revolves around the real-time acquisition of data from the environment as well as the adaptable control reactions that enhance system performance (Toha et al., 2025). The Application of IoT to libraries is still in its developmental phases. However, the concept has already been tested and proven efficient in smart homes, offices, and industrial complexes (Klavin, 2024). Some of the Key Enabling Technologies are LPWAN (Low Power Wide Area Network), Systems on Chip(SOC), and Intelligent Decision-Support Systems Platforms (Madakam et al., 2015).

Multiple researchers have examined the application of energy management systems combined with the Internet of Things (IoT) for public infrastructure. As an example, one study described the application of IoT for automating control of lighting and HVAC systems through occupancy-based automation (Gubbi et al., 2013). The authors argued that sensor networks can provide valuable data about user behavior that can be utilized for adjusting energy consumption dynamically (Chia-Hui et al., 2025). Another work analyzed the impact of spatially contextualized information blending environmental data along with energy analysis to achieve optimization in real-time performance (Balaji et al., 2013). All these studies corroborate the premise that systems based on sensors can optimize energy usage and reduce operational expenses, thereby making them desirable for library applications (Al-Saud & Al-Farsi, 2025).

Recently, researchers have been interested in integrating IoT with data analytics and machine learning for better predictive features in energy systems (El-Saadawi et al., 2024). There is evidence that combining smart metering and sensor data can facilitate predictive maintenance and load forecasting, alleviating energy waste as well as system downtime (Mohanty et al., 2016). This might be responsive lighting, automated scheduling of HVAC in the library, and user-specific comfort control (Anandhi et al., 2024). However, the research on IoT-LEMS frameworks that target libraries remains insufficient. This paper will address this gap by creating a particular architecture, founded on the application of IoT to energy-efficient, sustainable operations in a library environment (Ismail & Al-Khafajiy, 2025).

Inference: The literature evidence has revealed that IoT energy management systems have been created and studied across various applications, including smart homes, offices, and other industrial settings, which makes it reasonable to infer that they have enabled proper management of energy to promote the goals of energy efficiency, operational efficiency, and cost effectiveness. The individual technological capacities (LPWAN, SoC, and intelligent decision-support systems) were foundational to creating these systems. Additionally, machine learning and data analytics capabilities have allowed for adaptive and real-time control. Further, while the effectiveness of monitoring and sensor-based automation has been demonstrated, the literature highlights a gap in research being done on the application of these types of systems within the context of libraries. Therefore, there may be additional opportunities to develop IoT-enabled energy frameworks designed with library spaces for energy management goals for sustainable, responsive, and user-centered management.

III. METHODOLOGY

In designing an efficient framework for integrating IoT sensors into Library Energy Management Systems (LEMS), this study reviews previous works and finds issues related to scalability, real-time responsiveness, and heuristic control. Other systems lack robust responsiveness to dynamically changing occupancy and weather conditions, a requirement in energy-sensitive environments like libraries. Our approach solves these issues using a three-level framework of sensor data retrieval, intelligent data processing, and automatic control execution.

In the proposed model, temperature, humidity, occupancy, and light sensors are classified as IoT sensors and embedded into different regions of the library. These sensors constantly capture behavioral and environmental data, which are sent via low-power wireless interfaces such as Zigbee or LoRaWAN to the LEMS server. The system utilizes rule-based logic and predictive analytics to decide the most efficient energy configuration for the lighting, HVAC, and Ventilation systems. Effortless decisions to eliminate energy wastage while ensuring comfort are made constitutively by the system empowered by autonomous feedback loops. Moreover, trained lightweight machine learning models are built using historical data, which aid in energy demand forecasting, maintenance, and primary energy planning predictively.

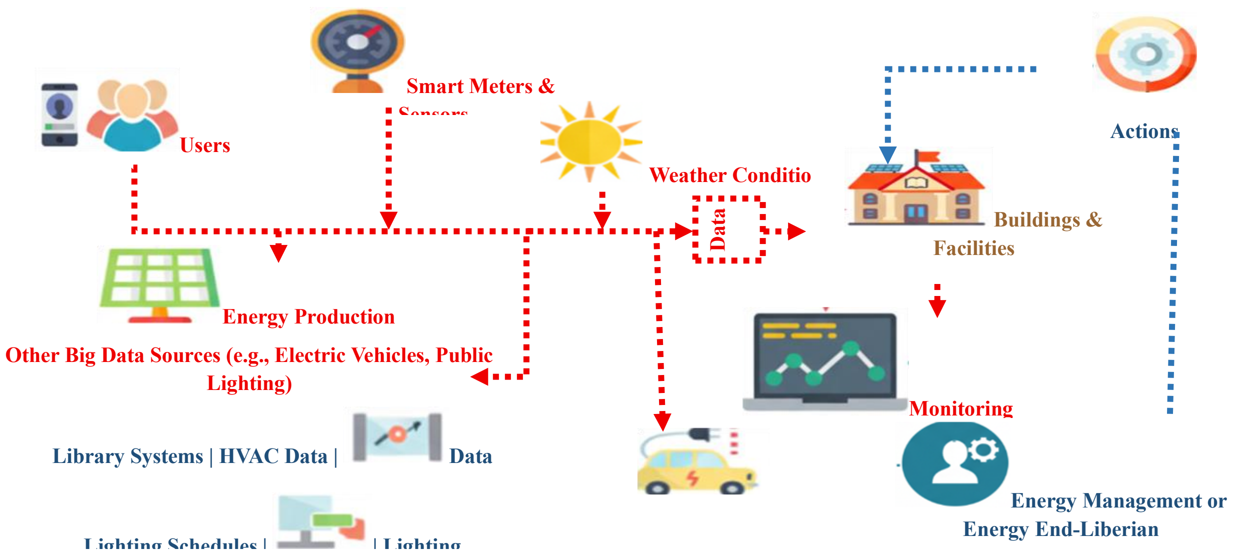

Fig. 1 IoT-Enabled Library Energy Management System Architecture

Fig 1 shows the architecture of a Library Energy Management System that is IoT-enabled. Smart meters and sensors under defined energy conditions, as well as external conditions such as weather, energy production, and other big data sources (for example, electric vehicles and public lighting), provide constant data streams. The data is further bound with library systems, such as lighting schedules and HVAC data, to examine energy consumption habits. This data is assimilated into a monitoring platform, examined by an energy manager or librarians in charge of resource efficiencies. Data-driven decisions are followed by action in the buildings and amenities in the library to provide for energy efficiency, waste reduction, and, on a more macro scale, sustainability.

3.1. Algorithms for Library Energy Management System

ML Prediction:

Artificial Neural Networks (ANNs) provide valuable forecasting of the future energy needs of buildings by recognizing trends in historical energy consumption data, weather, and occupant data. For libraries, this can be applied explicitly to predicting real-time needs for heating, ventilation, and air-conditioning (HVAC) systems and lighting systems, making them better able to schedule and monitor energy consumption based on user needs.

Support Vector Machines (SVMs) provide a way to classify and characterize energy consumption trends in library systems. Along with other data, they can be used as a method to find anomalies in such energy-consuming behavior, providing the tools to detect excessive energy consumption before rates are charged on usage, helping to minimize usage, ultimately lowering energy costs. The User-System Behaviors will be characterized as Excessive Users or average Users, and patterns of energy consumption will be monitored accordingly.

Decision Trees / Random Forests models may be used to develop a model of users in relation to their interaction with components of the system to develop an automated energy consumption behavior. Decision trees may also be used in a cybernetic approach in order to find solutions to automating lights and air-conditioning acts of users for rest, based on trends observed with previously collected occupancy data and models of occupancy.

Optimization:

Genetic Algorithm (GA) optimizes scheduling energy consumption through its genetic representation/algorithms based on natural selection. Libraries utilized it for optimizing energy consumption, limiting operating costs while maintaining thermal comfort and commercial activities in the library.

Particle Swarm Optimization (PSO), multiple energy sources such as renewable systems and grid supply can be coordinated. This will improve systems' flexibility in following load peaks and will facilitate more sustainable energy utilization.

Mixed-Integer Linear Programming (MILP) is capable of mathematically modeling the scheduling of loads driven by energy constraints. Libraries can utilize MILP to optimize the operations of lighting, HVAC, and digital devices in a resource-efficient way.

Control Algorithms:

Model Predictive Control (MPC) actively modifies library facilities by predicting future states of energy demand. This proactive modification ensures that HVAC and LED lighting can be controlled and operated with mitigated waste.

Fuzzy Logic Control creates a flexible option for decisions made under unknown conditions, like unexpected occupancy levels. Fuzzy logic can maintain energy efficiency without sacrificing the comfort of the users.

Data Processing & Anomaly Detection:

Clustering was introduced (K-Means, DBSCAN); tools such as clustering generated by machine learning can be utilized to analyze patterns in energy usage for the purpose of identifying inefficiencies and anomalies. Clustering can be a method to identify anomalies in library operations.

Principal Component Analysis is a method that can reduce the complexity of designing sensors for use in decision making through capturing the same irremediable features as analytic modeling, displaying similar variations, but increasing the speed in large data sets. PCA assists in the efficiency of monitoring large-scale library systems.

3.2. Proposed IoT-LEMS Framework Algorithm for Library Energy Optimization

Input: Sensor data (lighting, HVAC, occupancy, weather, energy price)

Output: Optimized energy schedule for library systems

Begin

  Collect real-time sensor data

  Forecast energy demand using ANN

  If an anomaly is detected by SVM, then

    Trigger alert and adjust controls

  End If

  Optimize energy schedule using GA/PSO

  Apply MPC to adjust HVAC and lighting dynamically

  Update the database with energy usage

End

This algorithm presents the systematic workflow of the IoT-enabled Library Energy Management System (IoT-LEMS), starting with collecting real-time data from various sensors (lighting, HVAC, occupancy, weather, and energy pricing) and then applying an Artificial Neural Network (ANN) to predict energy demand, a Support Vector Machine (SVM) to detect anomalies and enforce triggering functions, followed where optimization functions such as Genetic Algorithm (GA) or Particle Swarm Optimization (PSO) are performed to produce energy-efficient scheduling, then Model Predictive Control (MPC) dynamically adjusts HVAC and lighting to changing conditions, and finally, a database update is performed with the usage data calculations used to reflect continuous learning and improvement for sustainable operations.

Energy Efficiency Improvement Index (EEII)

To evaluate the effectiveness of the system, we introduce the Energy Efficiency Improvement Index (EEII):

$$EEII = \left(\frac{(E_{baseline} - E_{actual})}{E_{baseline}}\right) \times 100 \qquad (1)$$

Where in equation (1),

- E_b = Baseline energy consumption (before IoT-LEMS integration)
- E_b = Actual energy consumption (after IoT-LEMS integration)
- $EEII$ = Percentage improvement in energy efficiency

The Energy Efficiency Improvement Index (EEII) measures the integration of IoT sensors with the Library Energy Management System (LEMS) to evaluate the improvements made in energy efficiency quantitatively as a percentage.

The formula takes into consideration the energy usage before system implementation and compares it to the energy usage after. Using the provided terms, the value of energy saved is the difference between baseline consumption (E_b) and actual consumption (E_a). This difference, when divided by baseline consumption, yields the percentage of energy savings, which in turn, when multiplied by 100, gives the result in percentage form.

Energy Consumption Model

The total energy consumption of the library is the sum of all subsystems: lighting, HVAC, and equipment.

$$E_{total}(t) = E_{lighting}(t) + E_{HVAC}(t) + E_{equipment}(t)$$

Where:

- $E_{lighting}(t)$ = Energy consumed by lighting at time t
- $E_{HVAC}(t)$ = Energy consumed by HVAC at time t
- E (t) = Energy consumed by library equipment at time t

This equation summarizes total library energy consumption as the sum of its principal subsystems: lighting, HVAC, and Equipment. Each subsystem's energy is tracked over time for the purpose of monitoring dynamic changes. This method for modeling total energy consumption allows the library to manage and identify energy consumption regions and develop an energy management strategy.

This indicator shows how effective the system is in reducing energy consumption. The impact of real-time sensor feedback, intelligent control feedback, and adaptive controls implemented in the library infrastructure is verified with significantly high energy savings and improved performance, as indicated by increased values of EEII. The EEII can also be tracked at regular intervals (monthly or quarterly) to assess performance improvement or deviation detection over time.

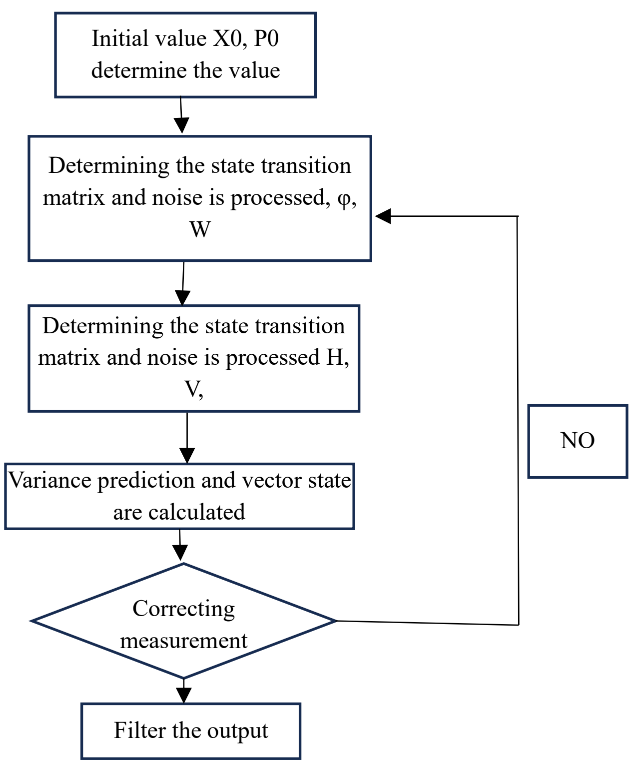

Fig. 2 Sensor Data Processing Flowchart for IoT-based Energy Management

Fig 2 depicts the flow of operations for an IoT-based Library Energy Management System as it processes the data received from its sensors. Other than setting the initial values for X 0 and P 0, the relevant state heuristics, error parameters, and certain key parameters need to be defined as well. The state transition matrix, along with the process noise covariance (W) matrix that needs to be set in order for future system state predictions to be made, is set next.

Sensor-Based Occupancy Adjustment

Let *O(t)* denote occupancy detected by IoT sensors (0 = empty, 1 = occupied). Lighting and HVAC can be dynamically controlled:

$$E_{lighting}(t) = P_{light} \cdot O(t) \cdot T$$

$$E_{HVAC}(t) = P_{HVAC} \cdot f\left(T_{set}, T_{room}\ (t)\right) \cdot O(t)$$

Where:

- P_{light}, P_{HVAC} = rated power of lighting and HVAC systems
- T_{set} = desired temperature
- $T_{room}(t)$ = measured room temperature
- $F\ (T_{set},\ T_{room}(t))$ = HVAC adjustment factor based on temperature difference

This model utilizes IoT sensor data to adjust lighting and HVAC energy usage according to real-time occupancy. When a space is occupied, lighting and HVAC are activated proportionally to power ratings and environmental conditions; when unoccupied, the systems remain off. The adjustment factor ensures that HVAC operation fits the difference between the setpoint and room temperature, reducing waste.

After completing the previous steps, the algorithm uses the sensor-enabling system state to compute the relating observation matrix along with measurement noise covariances, subsequently yielding (H, V) matrices. At this point, prediction of variance estimation as well as state vector estimation is performed in order to estimate the perceived level of energy required to be consumed at any point in time. The feedback approach enables progress derived from each measurement to update and enhance prior established estimate-based modifications. Passing the results through a filtering stage assures that the outcome aligns with the ideal deemed required control signals and further ensures accuracy pertaining to actual activations for the management mechanisms controlling lighting and HVAC, along with other energy expenditure systems. Energy optimization within library settings would be dynamically facilitated in real-time with the aid of this architecture.

Optimization Objective

Minimize total energy consumption while maintaining comfort levels:

$$\min_{u(t)} J = \sum_{t=1}^{T} E_{total}(t) + \lambda \cdot C_{discomfort}(t)$$

Where:

- $u(t)$ = control actions for lighting/HVAC at time t
- $C_{discomfort}(t)$ = discomfort index based on deviation from T_{set} or light levels
- λ = weight factor balancing energy savings vs comfort

The goal of the objective function is to minimize total energy used by the library while also ensuring comfort for the user. Periodically, control actions for the lighting and HVAC are optimized by balancing energy use and discomfort index (i.e., distance from an optimal or desired temperature or light level). The weight factor λ had the flexibility to encourage energy use or occupant comfort contingent upon the goals of the operation.

Predictive Control (MPC)

Use a predictive model for HVAC and lighting:

$$x(t+1) = Ax(t) + Bu(t) + w(t)$$

$$y(t) = Cx(t) + v(t)$$

Where:

- $x(t)$ = state vector (temperature, occupancy, light intensity)
- $u(t)$ = control vector (lighting ON/OFF, HVAC levels)
- $y(t)$ = measured outputs from sensors
- $w(t), v(t)$ = process & measurement noise
- A, B, C = system matrices defining dynamics

The MPC methodology employs a state-space model that predicts the future HVAC and lighting behaviour using the dynamics of the system and control inputs. The sensor feedback structure is incorporated to counteract deviations, in recognition of process and measurement noise. With this predictive strategy, proactive action can be taken to support the effective use of energy and comfort, identifiable through dynamic library conditions.

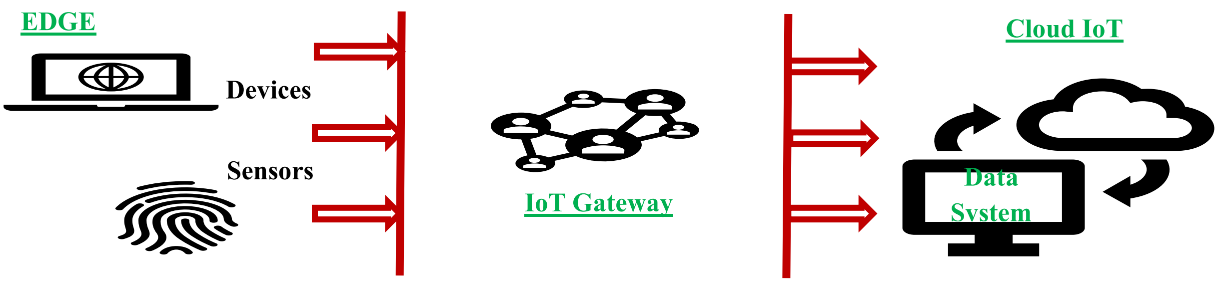

Fig. 3 System Architecture of IoT-LEMS for Smart Library Energy Management

Fig 3 displays the architecture of the proposed IoT-LEMS system, which consists of an Edge Layer, an IoT Gateway, and a Cloud IoT segment. On the Edge Layer of the library, sensors and edge devices for monitoring temperature, humidity, occupancy, and light levels are deployed on the library premises. These devices have limited resources but are efficient in data synthesis, preprocessing, and storing. As a link between edge devices and cloud infrastructure, the IoT Gateway fetches sensor data, does preliminary analysis, and sends processed packets over secure, latency channels. This layer performs local storage and caching for rapid decision-making. In the Cloud IoT Layer, Cloud components comprise storage databases, analytical engines, and user dashboards to permit real-time monitoring, reporting, and system enabling advanced data analytics, energy usage modelling, and decision-making algorithms.

This layered architecture enhances the energy management of the library to make it scalable, user-friendly, reduce operational costs, and build system security.

IV. Results And Discussion

The IoT-LEMS system of Library Energy Management was experimented with in the simulated conditions of a medium-sized public library. The simulation compared the pre- and post-installation of a sensor-based control system on the lighting, HVAC equipment, and equipment control subsystems in terms of energy consumption. A continuous observation of system data for a month was conducted to maintain system stability and reliability.

Total energy usage decreased markedly after implementing soft limits with real-time sensor data and automated control integration. We quantified performance with the Energy Efficiency Improvement Index (EEII). Performance was noted to be greatest in lighting due to occupancy-derived automation curbing surplus usage. Forecasted adaptive scheduling, which was moderated by the temperature and occupancy data, was also an advantage to the HVAC system. The system was characterized by significant energy saving and an increase in the responsiveness of operation.

Energy consumption metrics were quantified pre- and post-implementation. The Energy Efficiency Improvement Index (EEII) was calculated using the formula:

$$EEII\ (\%) = \frac{Baseline\ Energy - Post\ Implementation\ Energy}{Baseline\ Energy} \times 100$$

The proposed Library Energy Management System (IoT-LEMS) based on Internet of Things (IoT) has been tested with the help of the simulated environment of a medium-sized public library. The simulated environment consisted of such software tools as MATLAB/Simulink to develop system models and IoT data analysis, and hardware equipment such as occupancy sensors, smart thermostat, energy meters, and programmable relays to control the safety subsystem-HVAC (heating, ventilation, and air conditioning), lighting, and equipment. An observation of the system continuously will last thirty days to see how stable and reliable the system is.

TABLE I COMPARISON OF THE ENERGY CONSUMPTION BEFORE AND AFTER THE IMPLEMENTATION OF THE IOT-LEMS

Subsystem	Baseline (kWh)	After IoT-LEMS (kWh)	EEII (%)
Lighting	1200	780	35.00
HVAC	2100	1540	26.67
Equipment Control	900	720	20.00
Total	**4200**	**3040**	**27.62**

Table 1 presents a quantitative summary of energy consumption for each subsystem, both before and after the integration of IoT-LEMS. The Lighting subsystem showed the highest efficiency gain, with consumption dropping from 1200 kWh to 780 kWh, translating to a 35% reduction. The HVAC subsystem, which had the highest initial consumption of 2100 kWh, decreased to 1540 kWh, achieving an EEII of 26.67%. The Equipment Control subsystem demonstrated a more modest yet meaningful improvement, reducing energy usage from 900 kWh to 720 kWh, equivalent to a 20% efficiency gain. Overall, the total energy consumption fell from 4200 kWh to 3040 kWh, reflecting a system-wide energy efficiency improvement of 27.62%. These metrics validate the effectiveness of intelligent, sensor-driven automation in reducing operational energy demand in library settings.

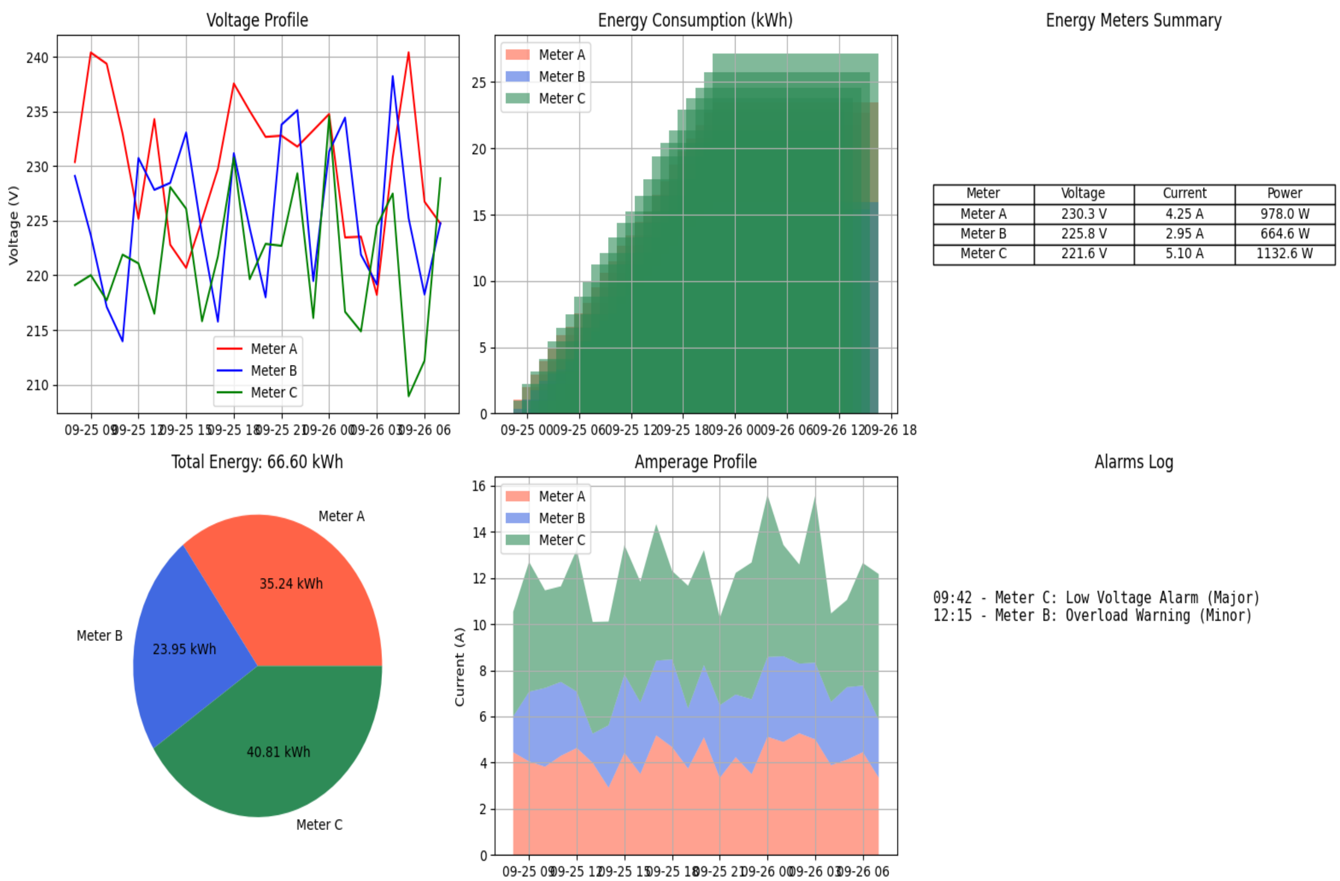

Fig. 4 Real-Time Monitoring of Library Energy Consumption via IoT Sensor Integration

Fig 4 gives an overview of energy consumption in a library through IoT sensors to monitor voltage, current, and energy use from several meters. The voltage profile chart symbolizes the variation in voltage from the electrical supply. The energy and physical consumption pie charts monitor energy consumption and verbalize the distribution of consumption across meters. The amperage profile illustrates current in various magnitudes over time to assist in identifying the periods of demand. The summary table of energy meters includes the highlighted metrics, and the alarm logs include any events of interest, for example, low voltage and overload conditions. The visualization thus supports very effective monitoring of energy consumption and allows for ongoing maintenance, as needed, promptly.

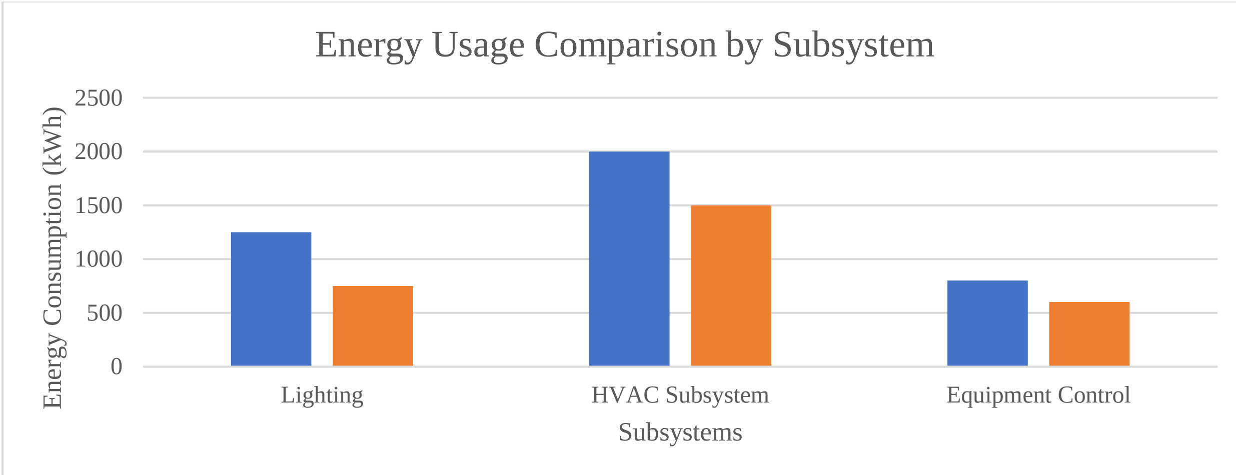

Fig. 5 Energy Usage Comparison by Subsystem

Fig 5 visually reinforces the trends outlined in the table. Each subsystem is represented with two bars: one indicating baseline energy usage and the other showing post-implementation consumption. The most noticeable visual drop is observed in the Lighting subsystem, clearly illustrating the effectiveness of occupancy-based controls. The HVAC subsystem, despite its overall high energy consumption, exhibits a significant reduction, confirming that adaptive temperature and ventilation scheduling driven by sensor data is highly effective. Although the Equipment Control subsystem shows a relatively smaller decrease, it still contributes to overall efficiency. The graph offers a clear, at-a-glance understanding of subsystem-level performance improvements and supports the argument for adopting IoT-LEMS in similar environments.

The performance analysis has shown that the IoT sensors in combination with automated control can increase energy performance by an order of magnitude. The system can be verified, repeated, and scaled, which means that it may be applied to other library scenarios. Machine learning may be further used in the process to apply predictive control to the energy scheduling process, and other subsystems (e.g., security or digital asset management) may be added to it.

V. Conclusion

This work paper has shown how Internet of Things (IoT) technologies can be incorporated into the Library Energy Management Systems (LEMS) and used to attain better energy efficiency, sustainability, and operational intelligence. The application of sensor-based monitoring and automation systems within the proposed IoT-LEMS framework resulted in a significant decrease in energy usage in the most important subsystems, including lighting, HVAC, and equipment control, as well. The results of the simulation indicated a total improvement of around 27.62 percent in the energy efficiency. The lighting systems recorded the maximum individual efficiency gain compared to all the systems. The IoT energy management technology is the exact solution to the needs of such systems, as it allows real-time measurements, monitoring, predictive analytics, and adaptive control. This, by extension, assists in lowering the cost of operations of the system and environmental damage. The possible consequences of this study are enormous. The concept is adaptable to other types of libraries and improved with other subsystems, such as security, user tracking, and digital asset management. The framework will also include autonomy of a self-governing energy system with predictive analysis and machine learning algorithms in interface C. The live condition tests will need to refine the accuracy, scalability, and interoperability of the system, which should be further researched.

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