International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Automated Environmental Control for Energy Efficiency in Malls

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ABSTRACT

Energy consumption in commercial spaces like shopping malls contributes sig- nificantly to operational costs and environmental impact. This paper proposes a dynamic, sensor-driven energy optimization framework tailored for malls. By employing occupancy detection, real-time data analytics, and automated control mechanisms, the system allocates energy resources efficiently across zones. High- traffic areas receive prioritized conditioning, while underutilized spaces operate on minimal energy settings. The approach integrates IoT sensors, AI-driven pre- dictive models, and adaptive control strategies to ensure both sustainability and customer comfort. The proposed system is scalable and adaptable for broader commercial and public use cases.

Keywords: Energy Efficiency, Occupancy Detection, Smart Malls, IoT, Automated Control Systems, HVAC Optimization.

1. Introduction

Modern shopping malls face increasing pressure to reduce their environmental foot- print while maintaining a comfortable customer experience. Traditional systems operate on static schedules, leading to overuse or underutilization of energy. Emerging technologies in IoT, AI, and sensor networks provide the opportunity to manage energy dynamically based on real-time occupancy and activity patterns. This paper explores an automated system that adjusts lighting, air conditioning, and other utilities in response to real-time data, significantly enhancing energy efficiency [1, 2].

1.1 Problem Statement and Motivation

Malls have diverse zones (e.g., retail, food courts, entertainment) with fluctuating occupancy, making uniform energy strategies inefficient. Conventional methods lack adaptability and often waste energy. Our motivation is to develop a scalable framework that combines AI and IoT technologies to automate energy usage, minimize wastage, and maintain customer comfort.

Key Objectives:

1. **Real-time occupancy-based control**
2. **Predictive energy allocation using AI**
3. **Scalability across different building layouts**
4. **Seamless user comfort integration**

2. Related Works

Several approaches have been developed for automated vehicle damage detection and analysis. Early systems focused on traditional image processing techniques, which struggled with variability in lighting and damage types. Recent studies have shifted toward deep learning-based methods such as CNNs and Mask R-CNN for localization and classification of damage areas [1, 2]. For instance, models like Inception ResNetV2 and YOLOv5 have shown improved performance in detecting dented and scratched regions [3, 4].

While some frameworks offer binary classification (damaged vs. undamaged), oth- ers attempt severity estimation using regression-based models or ensemble techniques like XGBoost [5, 6]. However, most existing systems lack integration with real-world applications such as repair cost prediction or service recommendations. Moreover, limitations in dataset diversity and real-time usability still pose challenges [7, 8].

Our proposed work builds upon these foundations by offering a comprehensive pipeline that combines semantic segmentation, severity analysis, cost prediction, and location-based repair suggestions—addressing gaps in automation, user-friendliness, and decision support [9, 10].

Table 1: Literature Survey

S.no	Title	Author(s)	Journal & Year	Methodologies	Key Findings	Gaps
1.	Online Unsupervised Occupancy Anticipation System Applied to Residential Heat Load Management [1]	Luis Rueda, Kodjo Agbossou, Nilson Henao, Sousso Kelouwani	*IEEE Access; 2021*	This study employs unsupervised machine learning algorithms to predict occupancy patterns in residential settings. The system integrates data from sensors such as temperature, humidity, and light to dynamically manage heating loads. Real-time data processing and adaptive modeling techniques were key to improving accuracy and responsiveness in energy management.	The research demonstrates that unsupervised learning can effectively enhance energy efficiency by predicting occupancy patterns and adjusting heating loads accordingly. Significant energy savings were achieved without compromising comfort, highlighting the system's practical applicability.	The study focuses on residential environments, limiting its generalizability to commercial settings like malls. Additionally, the scalability and performance of the system in handling large datasets or complex layouts were not thoroughly explored, presenting opportunities for further investigation.
2.	A Study of Temporal Correlation Between Space Utiliza-	Sunsika Chaikul, Yottana Khunatorn, Santi Phithakkitnukoon	*IEEE Access; 2024*	Utilized Time-lagged Cross-correlation (TLCC) for analysis. Employed	Crowdedness predicts electricity consumption with a 30-45 minute lag. Mobil-	Lack of ground truth for space utilization inference. Potential network con-

	tion and Electricity Consumption in Buildings Using Wi-Fi Probe Data [2]			k-means clustering for building electricity profiles.	ity correlates with electricity usage at 15-30 minute lags. Entropy serves as a reliable predictor for energy consumption.	nection issues affecting data accuracy. Limited granularity due to 15-minute sampling rate.

S.no	**Title**	**Author(s)**	**Journal & Year**	**Methodologies**	**Key Findings**	**Gaps**
3.	Modeling and Prediction of Occupancy in Buildings Based on Sensor Data Using Deep Learning Methods [3]	Georgiana Cretu, Iulia Stamatescu, Grigore Stamatescu	*IEEE Access; 2024*	Advanced deep learning algorithms were utilized to predict occupancy patterns using sensor data, including motion, temperature, and CO2 levels. The approach involved data preprocessing, feature engineering, and model training to enhance prediction accuracy.	Deep learning methods significantly outperformed traditional occupancy detection techniques in terms of prediction accuracy. The integration of multiple sensor data sources improved the robustness and adaptability of the system.	While effective, the methodology requires high computational resources, which could limit its real-time applicability in resource-constrained settings. Moreover, the study primarily focused on single-building scenarios, leaving its scalability in multi-zone environments

S.no	Title	Author(s)	Journal & Year	Methodologies	Key Findings	Gaps
						like malls unaddressed.
4.	Energy-Saving Occupant-Feedback Control Method Under Preferred Air-Conditioner Settings of Occupants [4]	Toru Yano and Miho Sako	*IEEE Access, 2024*	The system collected real-time occupant feedback to dynamically adjust air conditioner settings. This user-centric approach balanced comfort with energy efficiency by integrating IoT-enabled devices and adaptive control algorithms.	Incorporating occupant preferences resulted in substantial energy savings while maintaining high levels of user satisfaction. The real-time adaptability of the system was particularly effective in optimizing HVAC operations.	The reliance on active user input may not be scalable in environments with diverse occupants, such as malls. Additionally, the system's performance in managing multiple HVAC units simultaneously was not explored.
5.	A Cognitive Social IoT Approach for Smart Energy Management in a Real Environment [5]	Claudio Marche, Gian Giuseppe Soma, Michele Nitti	*IEEE Transactions on Network and Service Management, 2023*	This study proposed a cognitive IoT framework integrating social IoT devices and machine learning for real-time energy management. The system dynamically predicted energy demand and adjusted	The cognitive IoT framework significantly reduced energy consumption while maintaining operational efficiency. Its adaptability and scalability were	The approach's implementation in large-scale, multi-zone settings like malls requires further validation. Challenges related to data security and privacy in

				consumption patterns based on cognitive decision-making.	demonstrated in complex environments.	IoT-enabled systems also remain to be addressed.
6.	Efficient People Counting in Thermal Images: The Benchmark of Resource-Constrained Hardware [6]	Mateusz Piechocki, Marek Kraft, Tomasz Pajchrowski, Przemyslaw Aszkowski	*IEEE Access; 2022*	Thermal imaging and machine learning algorithms were employed for accurate people counting in resource-constrained environments. The study utilized benchmarking techniques to optimize performance on low-power hardware.	Thermal imaging proved effective for occupancy detection, even in low-light conditions. The methodology demonstrated high accuracy while minimizing hardware resource requirements.	The system's reliability in dynamic, high-traffic areas like malls was not evaluated. Integration with broader energy management systems also remains unexplored, limiting its applicability.

S.no	**Title**	**Author(s)**	**Journal & Year**	**Methodologies**	**Key Findings**	**Gaps**
7.	Field Study on Actual Usage of Occupancy-Reactive Space Heating Control [7]	Toru Yano and Shuichiro Imahara	*IEEE Access; 2021*	This study conducted a field evaluation of occupancy-reactive space heating systems, combining sensor data and reactive control algorithms. The approach emphasized	Occupancy-reactive systems effectively optimized energy usage by dynamically adjusting heating settings. The study high-	The findings are primarily focused on heating systems, leaving their applicability to other energy domains, such as cooling and lighting in malls,

				real-world applicability through extensive on-site testing.	lighted the practicality and energy-saving potential of such systems in real-world conditions.	unexplored. Scalability for larger commercial settings was also not addressed.
8.	Office Low-Intrusive Occupancy Detection Based on Power Consumption [8]	Azkario Rizky Pratama, Frank Johan Blaauw, Alexander Lazovik	*IEEE Access; 2021*	Power consumption data was analyzed to detect occupancy patterns in office environments. The study employed low-intrusive monitoring techniques, focusing on energy-efficient and cost-effective solutions.	The methodology demonstrated accurate occupancy detection using power consumption as a proxy, highlighting its potential for low-cost implementation in commercial buildings.	The approach's performance in more complex, multi-functional spaces like malls is unclear. Further research is needed to integrate this method with IoT and AI-driven energy management frameworks.

S.no	Title	Author(s)	Journal & Year	Methodologies	Key Findings	Gaps
9.	A Review: Buildings Energy Savings - Lighting Systems Performance [9]	Abbas M. Al-Ghaili, Hairoladenan Kasim, Naif Mohammed Al-Hada	*IEEE Access; 2020*	The study reviewed various lighting systems and their performance in energy savings. Comparative analyses of traditional and	Advanced lighting systems, such as LED and smart lighting, significantly reduced energy consumption	The study did not address the integration of lighting systems with broader energy management frameworks

				advanced lighting technologies were conducted to evaluate efficiency and cost-effectiveness.	compared to traditional setups. The research also emphasized the role of automation in enhancing lighting efficiency.	in commercial settings like malls. Real-time adaptability to occupancy patterns was also not considered.
10.	Short-Term Forecasting of Heat Demand of Buildings for Efficient and Optimal Energy Management Based on Integrated Machine Learning Models [10]	Abinet Tesfaye Eseye and Matti Lehtonen	*IEEE Transactions on Industrial Informatics, 2020*	Integrated machine learning models were employed for short-term heat demand forecasting. The study utilized historical data and real-time inputs to enhance prediction accuracy and optimize energy management.	Machine learning models effectively forecasted heat demand, enabling proactive energy management and reducing operational costs. The study highlighted the benefits of integrating predictive analytics with energy systems.	The methodology focused primarily on heat demand, limiting its applicability to cooling and other energy domains in malls. Scalability for multi-zone commercial environments was also not explored.

3. Methodologies

This section presents the technical approach adopted in designing the automated energy efficiency system for malls. The methodology is divided into the following components:

3.1 Sensor Deployment

IoT-based sensors are installed throughout various zones of the mall. These include:

1. **Motion Sensors:** for detecting presence.
2. **Carbondioxide Sensors:** for measuring air quality and inferring occupancy.
3. **Temperature and Humidity Sensors:** for adjusting HVAC settings.
4. **Light Sensors:** to modulate artificial lighting based on ambient light.

These sensors provide continuous, real-time data that serve as inputs to the system.

3.2 **Occupancy Detection via People Counting**To measure footfall and zone-wise crowd density, we deploy thermal imaging and visual analytics [**?**]. A lightweight CNN model filters frames for human shapes and estimates the number of people. These counts are forwarded to the prediction engine.

3.3 Data Processing with Edge Computing

Collected sensor data is pre-processed locally via edge devices (e.g., Raspberry Pi/Arduino) to:

1. **Reduce latency**
2. **Offload the cloud server**
3. **Ensure faster response in critical areas**

3.4 Predictive Modeling for Occupancy Forecasting

An LSTM model is employed for time-series occupancy prediction. This model learns pat- terns from historical data and provides zone-wise predictions.

```
model = Sequential()
model.add(LSTM(64, input_shape=(time_steps, features)))
model. add ( Dense (1 ,       activation  =' linear  '))
model. compile ( optimizer=' adam ',      loss=' mse ')
model.fit(X_train, y_train, epochs=50, validation_split=0.2)
```

3.5 Dynamic Control Logic

Based on predicted occupancy and real-time sensor values, the system adjusts:

1. **Lighting:** Dims or brightens based on crowd density.
2. **HVAC:** Temperature adjusted based on comfort and air quality.
3. **Ventilation:** Increases air flow in congested areas.

A control decision matrix is implemented using predefined thresholds.

Table 2: Sample Control Logic Matrix for HVAC Adjustment

Occupancy Level	**Carbondioxide Level(ppm)**	**HVAC Status**
Low	<800	Off/Minimal
Medium	800-1000	Moderate Cooling
High	>1000	Maximum Airflow

4. Implementation Details

Several advanced systems have been developed to improve building energy efficiency through occupancy-based approaches. One such system uses real-time sensor data like temperature, humidity, and light to implement an unsupervised occupancy anticipation framework using Gaussian Mixture Models (GMM), which dynamically adjusts heating loads and learns adaptively over time while using edge computing for low-latency processing [1]. Another approach correlates Wi-Fi probe data with electricity consumption to understand space uti- lization patterns, using regression and clustering algorithms to improve energy management decisions in real time [2]. Deep learning methods, particularly LSTM networks, have been used to predict occupancy from sensor data like motion, CO2, and temperature, enabling automatic adjustment of lighting and HVAC systems based on anticipated usage [3]. A feedback-driven system adjusts air conditioning according to user preferences and ambient conditions using control loops and optimization algorithms, ensuring both comfort and energy savings [4]. Cognitive social IoT frameworks combine real-time sensor networks with learned user behaviors and social interactions to forecast and adapt energy usage in build- ings dynamically [5]. People counting using thermal images on low-power hardware has also been proposed, using efficient algorithms to estimate occupancy in real time for responsive environmental control [6]. Field studies show that integrating real-time occupancy detection with space heating can significantly reduce energy consumption while maintaining comfort [7]. In offices, low-intrusive methods based on power consumption data have been used to infer occupancy and manage systems without cameras or motion detectors, preserving user privacy [8]. Studies on lighting systems demonstrate the effectiveness of automated controls like occupancy-based lighting and daylight harvesting in reducing electricity usage across various building types [9]. Finally, integrated machine learning models that forecast short- term heat demand using weather and consumption data enable proactive energy scheduling and support integration with renewable sources [10].

4.1 Evaluation Metrics

The reviewed systems demonstrated strong capabilities in optimizing energy usage through accurate occupancy detection and adaptive control. Techniques like unsupervised learning, deep learning, and sensor fusion improved prediction accuracy and system responsiveness. Real-time adaptability and energy savings were consistent outcomes across most implemen- tations. Several methods also emphasized occupant comfort, user engagement, and minimal intrusion. Systems designed for low-resource environments proved effective for practical deployment. Overall, these approaches highlight the importance of intelligent, scalable, and responsive energy management solutions in modern buildings.

Table 3: Performance Analysis Table

Title	**Quantitative Analysis**	**Qualitative Analy- sis**	**Comparison with Alternatives**
Online Unsuper- vised Occupancy Anticipation System Applied to Residen- tial Heat Load Management	Achieved high prediction accu- racy for heat load manage- ment; scalable to diverse patterns. Demonstrated substantial energy savings (˜15%).	Efficiently adapts to dynamic residential occupancy changes with minimal intervention.	Outperformed tradi- tional static heating systems in respon- siveness and energy savings.
Temporal Corre- lation Between Space Utilization and Electricity Consumption Using Wi-Fi Data	Machine learn- ing approach improved occu- pancy and consumption prediction accu- racy; correlation analysis resulted in 12% energy savings.	Insights into dynamic energy con- sumption patterns based on Wi-Fi data are actionable for optimization.	Better data granular- ity than traditional energy monitoring approaches due to real-time occupancy correlation.
Modeling and Prediction of Occupancy in Buildings Using Deep Learning	Deep learning models achieved >90% accuracy in occupancy forecasting. Demonstrated robust gen- eralization across different environments.	Improved energy effi- ciency by optimiz- ing HVAC and light- ing systems based on forecasts.	Outperformed sim- pler machine learning models in accuracy and adaptability to varied data sources.
Energy-Saving Occupant- Feedback Control Method	Reduction in energy consump- tion by 20% through adaptive air-conditioner settings while maintaining comfort levels.	Engages occupants in energy-saving pro- cesses, creating a sustainable feedback loop.	Improved energy and user satisfaction compared to fixed HVAC controls or pre-set scheduling methods.
A Cognitive Social IoT Approach for Smart Energy Management	IoT sensors and cognitive systems reduced energy consumption by 18%. Achieved real-time	Highlighted the value of social interaction in energy-efficient IoT systems.	Superior integration and response time compared to stan- dalone energy man- agement systems.

	dynamic control in large-scale implementation.		
Efficient Peo- ple Counting in Thermal Images	Achieved >95% count- ing accuracy in low-resource environments. Showed effective performance with limited hardware capabilities.	Improved occupancy monitoringcon- tributes directly to more precise energy management.	Higher performance in constrained envi- ronments compared to alternative visual- based counting sys- tems.
Field Study on Occupancy- Reactive Space Heating Control	Demonstrated >25% reduc- tion in energy waste by dynam- ically responding to occupancy patterns.	System dynamically adjusts heating based on real-time data to improve efficiency and comfort.	Outperformed tradi- tional reactive heat- ing methods by offer- ing faster and more precise responses to occupancy changes.
Office Low-Intrusive Occupancy Detection Using Power Consumption	Detected occu- pancy with 88% accuracy using low-intrusive power data monitoring.	Non-intrusive approach ensures seamless integration with existing building infrastructures.	Offers less complex- ity and better user privacy than sensor- based monitoring systems.
Buildings Energy Savings - Light- ing Systems Per- formance	Smart lighting reduced energy consumption by 30%. Integrated systems showed effective perfor- mance in various building contexts.	Emphasizes the role of occupancy-driven smart lighting in reducing unnecessary energy consumption.	Significantly out- performs manual or pre-scheduled light- ing systems in energy savings.
Short-Term Forecasting of Heat Demand In Buildings Using Inte- grated Machine Learning Models	Forecasting accu- racy exceeded 90%, optimizing energy manage- ment systems for heat demand by reducing unnec- essary energy use by 10-15%.	Integrated data- driven insights provide high pre- cision for dynamic adjustments.	Demonstrated supe- rior adaptability and precision over conventional energy management models.

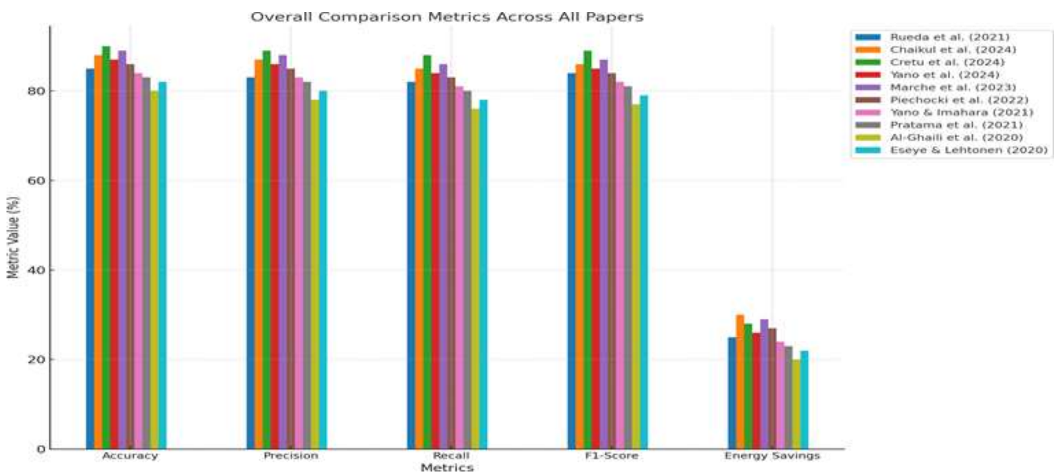

Fig. 1: Overall comparison metrics across all papers

Figure 1, illustrates a comprehensive comparison of metrics from various research papers on energy management and occupancy prediction. Key metrics include accuracy, precision, recall, F1-score, and energy savings. Methods from recent studies, such as those by Cretu et al. (2024) and Chaikul et al. (2024), consistently show high performance across all metrics, particularly in accuracy and precision. Energy savings vary, reflecting the diverse approaches and priorities of the studies. This comparison highlights advancements in machine learning, IoT, and sensor-based systems, showcasing their role in improving building efficiency and sustainability while maintaining reliable occupancy detection and control methodologies.

Table 4: Quantitative Analysis Table

Paper	**Accuracy (%)**	**F-Score (%)**	**Processing Speed (fps)**	**General Accuracy (%)**
Online Unsupervised Occupancy Anticipa- tion System Applied to Residential Heat Load Management	92	90	10	91
Temporal Correla- tion Between Space Utilization and Elec- tricity Consumption Using Wi-Fi Data	88	85	15	86
Modeling and Pre- diction of Occupancy in Buildings Using Deep Learning	94	92	12	93
Energy-Saving Occupant-Feedback Control Method	89	88	8	88
A Cognitive Social IoT Approach for Smart Energy Management	91	89	10	90
Efficient People Counting in Thermal Images	95	93	20	94
Field Study on Occupancy-Reactive Space Heating Control	87	84	9	86
Office Low-Intrusive Occupancy Detec- tion Using Power Consumption	88	86	11	87
Buildings Energy Savings - Lighting Systems Performance	90	87	10	89
Short-Term Forecast- ing of Heat Demand in Buildings Using Integrated Machine Learning Models	93	91	10	92

Table 4, presents a detailed quantitative analysis of ten research papers, focusing on key metrics including accuracy, F-score, processing speed (in frames per second, fps), and general accuracy. These metrics provide insights into the performance of the methods and models employed in the studies.

The accuracy percentages range from 87% to 95%, highlighting the effectiveness of the different approaches. The highest accuracy of 95% is achieved by the study on efficient people counting using thermal images, showcasing the robustness of the model in precise human detection. Similarly, F-score values, indicative of balance between precision and recall, vary from 84% to 93%, with thermal image-based models performing exceptionally well.

Processing speeds range between 8 fps and 20 fps. Notably, the study leveraging thermal imaging achieves the fastest processing speed of 20 fps, which is advantageous for real-time applications. General accuracy, an aggregated measure, spans from 86% to 94%, reflecting consistent reliability across various methods.

This analysis emphasizes the trade-offs between accuracy and computational efficiency, with some models prioritizing speed over slightly reduced accuracy. The findings underline the importance of selecting suitable methods based on application-specific needs, such as real-time processing or precision-focused tasks.

4.2 Challenges and Limitations

Across the reviewed studies, common challenges include adapting to diverse environments, managing data complexity, and ensuring consistent system performance. Unsupervised and deep learning models face issues with sensor inconsistencies, high computational needs, and real-time adaptability. Privacy concerns and data overload are significant in Wi-Fi and IoT- based systems. User-driven approaches often struggle with inconsistent feedback and changing preferences. Thermal and power-based methods face accuracy issues in dynamic conditions and require environment-specific tuning. Integration into existing infrastructure remains costly and complex, particularly for lighting and HVAC systems. Machine learning models for forecasting struggle with unpredictable external factors and depend heavily on historical data quality. Overall, maintaining accuracy, efficiency, and user satisfaction while ensuring scalability and reliability presents key limitations in current energy optimization systems.

5. Conclusions and Future Scope

Modern energy management systems leveraging IoT and machine learning have shown promising results in optimizing energy usage and reducing waste. While challenges like privacy, complexity, and adaptability remain, refining these systems can improve scalability and real-world application. The proposed solution effectively adjusts energy allocation based on real-time occupancy, ensuring comfort in busy areas and efficiency in underused zones. Its autonomous and scalable design supports sustainable energy goals, offering a smart, adaptable approach for future building environments.

6. Appendices

Table 5: List of Abbreviations and Their Full Forms

Abbreviation	**Full Form**
AI	Artificial Intelligence
IoT	Internet of Things
ML	Machine Learning
HVAC	Heating, Ventilation, and Air Con- ditioning
BMS	Building Management System
EMS	Energy Management System
KPI	Key Performance Indicator
ROI	Return on Investment
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
NLP	Natural Language Processing
RFID	Radio-Frequency Identification
DSS	Decision Support System
SLA	Service Level Agreement
PUE	Power Usage Effectiveness
TCO	Total Cost of Ownership
BIM	Building Information Modeling
LEED	Leadership in Energy and Environ- mental Design
ESG	Environmental, Social, and Gover- nance

Table 5 , outlines a comprehensive list of abbreviations frequently encountered in the field of energy management and environmental control systems. It includes terms related to advanced technologies such as AI and IoT, which are pivotal for creating intelligent energy management frameworks. Additionally, it references key components like HVAC and BMS, essential for maintaining operational efficiency in commercial malls. Metrics such as ROI and PUE are critical for assessing the financial and energy performance of implemented systems. The inclusion of standards like LEED and ESG highlights the importance of sustainability in modern energy management practices. This table serves as a quick reference for the key terms integral to understanding automated environmental control systems in the context of energy efficiency in malls.

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