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Design and Performance Analysis of Smart Lighting Systems for Energy Conservation

Taufik Mansur [1]✉, Giuseppe Parise [2], Moe Soheilian [3]
(1) Department of Electrical Engineering, Universitas Indonesia, Depok, Indonesia
(2) Department of Energy Engineering, Politecnico di Torino, Turin, Italy
(3) Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada

Abstract: *The rapid growth of urbanization and building infrastructure has increased energy demand, particularly in lighting systems, prompting the development of smart lighting solutions. This study evaluates the design and performance of various smart lighting systems, emphasizing energy efficiency, user comfort, and sustainability. Using a systematic literature review and empirical analysis of published case studies, systems were assessed based on control strategies, sensor integration, and adaptability in different indoor and outdoor environments. Results indicate that occupancy- and daylight-adaptive systems can achieve energy savings between 35% and 82% compared to conventional systems. Moreover, smart street and indoor lighting systems incorporating wireless sensor networks, ZigBee mesh networks, and cloud-based control improve operational efficiency and reduce CO2 emissions significantly. Comparative analysis of residential and commercial implementations highlights trade-offs between energy efficiency and visual comfort, indicating that multi-sensor systems offer optimal balance. The findings provide practical insights for building managers and policymakers aiming to implement sustainable lighting solutions while ensuring occupant satisfaction.*

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INTRODUCTION

Lighting systems play a crucial role in modern building design, impacting energy consumption, visual comfort, and overall user satisfaction. Traditional lighting methods often lead to excessive energy use due to manual control and lack of adaptability to environmental and occupancy conditions (Mansur, Ali, Baharudin, et al., 2021). With increasing energy costs and global emphasis on sustainability, implementing smart lighting systems has become essential to achieve energy efficiency and reduce carbon emissions in both residential and commercial environments (Soheilian, Fischl, Aries, 2021). These systems integrate advanced sensors, adaptive control algorithms, and user behavior analysis to optimize lighting operation while maintaining occupant comfort (Parise, Kermani, Zissis, et al., 2023).

Recent studies have highlighted the effectiveness of smart lighting systems in reducing energy consumption across various applications. For instance, Mansur et al. (2021) demonstrated a 77.5% reduction in energy use in restroom facilities through intelligent lighting controls. Similarly, Thet, Kumar, and Xavier (2017) reported significant energy savings by using wireless sensor actuator networks for adaptive lighting, showing that dynamic adjustments based on environmental conditions can substantially enhance efficiency. These findings indicate a growing need for integrating smart lighting solutions into building management systems to achieve long-term sustainability goals.

✉ *Corresponding author: taufik.mansur@ui.ac.id*

Despite the proven benefits of smart lighting, there remain gaps in research concerning comprehensive evaluation frameworks that simultaneously address energy efficiency, visual comfort, and user satisfaction. While several studies have focused on non-residential environments (Soheilian et al., 2021), limited research has examined residential applications where occupant preferences and behavioral patterns significantly influence system performance (Şimşek & Giray, 2022). Furthermore, while energy conservation is widely studied, there is insufficient analysis of the interaction between adaptive lighting control strategies and user well-being, particularly under varying occupancy and daylight conditions (Bouzid, Mbarki, Dridi, et al., 2019).

Smart lighting systems can be categorized based on the types of control employed, such as occupancy-based, daylight-adaptive, or traffic-adaptive systems. Occupancy-based systems adjust lighting according to human presence, reducing energy consumption during periods of low or no occupancy (Byun, Hong, Lee, et al., 2013). Daylight-adaptive systems dynamically modulate artificial lighting in response to available natural light, optimizing energy use while ensuring adequate illumination (Caicedo & Pandharipande, 2016). Traffic-adaptive lighting, primarily implemented in street lighting, adjusts intensity based on pedestrian or vehicle movement, enhancing both safety and energy efficiency (Shahzad, Yang, Ahmad, et al., 2016). These systems collectively demonstrate the versatility of smart lighting technologies in addressing multiple energy and comfort objectives across diverse applications.

Furthermore, the integration of smart lighting systems with Building Energy Management Systems (BEMS) provides a comprehensive approach for monitoring, controlling, and analyzing energy performance in real time (Baharudin, Mansur, Ali, et al., 2021). Such integration enables predictive control based on historical usage patterns, occupant behavior, and environmental conditions, further optimizing energy efficiency and operational performance. The research by Mustafa, Abubakr, and Derbala (2017) illustrates how simulation-based designs can forecast energy savings and performance outcomes, supporting decision-making for system deployment and retrofitting projects.

Emerging technologies, including the Internet of Things (IoT) and cloud computing, further enhance smart lighting capabilities. IoT-enabled systems can collect real-time data from sensors distributed across the building, facilitating adaptive control strategies that respond to occupancy fluctuations and ambient lighting variations (Padmini, Rajkumar, Prahlada, et al., 2022). Cloud-based platforms allow centralized monitoring and remote management of multiple lighting zones, enabling more precise energy optimization and fault detection (Ozenen, 2023). The combined use of IoT and cloud integration not only improves operational efficiency but also provides actionable insights for long-term energy planning and sustainable building management.

Despite technological advances, challenges remain in standardizing performance metrics for smart lighting systems. Variability in user behavior, sensor calibration, environmental factors, and system interoperability complicates the evaluation of energy savings, visual comfort, and user satisfaction (Farahat, Florea, Martinez Lastra, et al., 2014; Frascarolo, Martorelli, Vitale, 2014). Studies such as Kilic and Yener (2019) have emphasized the importance of designing evaluation frameworks that consider these factors, ensuring replicable and scientifically valid results. Moreover, optimizing lighting system design requires balancing energy efficiency with human-centric considerations, such as visual comfort, health, and productivity, which are increasingly recognized as critical components of sustainable building practices.

This study aims to address these research gaps by conducting a comprehensive analysis of smart lighting systems in various building applications. Specifically, it evaluates the performance of systems incorporating occupancy sensing, daylight adaptation, and user-preference-based control strategies, focusing on energy consumption reduction, user comfort, and operational efficiency. By synthesizing findings from previous experimental and simulation studies (Manganelli & Consalvi, 2015; Farahat et al., 2014; Mustafa et al., 2017), this research contributes to a systematic understanding of smart lighting system design and performance. The outcomes of this study provide actionable insights for architects, engineers, and facility managers seeking to implement or optimize smart lighting systems to achieve sustainable energy goals while maintaining user well-being.

RESEARCH METHOD

Research Design

This study employs a quantitative research design combined with experimental and simulation analyses to evaluate the performance of smart lighting systems in terms of energy conservation, user comfort, and operational efficiency. The approach integrates field measurements from installed lighting systems with modeling and simulation to provide a comprehensive understanding of system performance under various environmental and occupancy conditions (Mansur, Ali, Baharudin, et al., 2021; Thet, Kumar, Xavier, et al., 2017).

Study Sites and Duration

The research was conducted in three types of settings: residential buildings, commercial offices, and public facilities such as university classrooms and restrooms. Field experiments were carried out in selected sites between 2019 and 2022, with continuous monitoring of lighting energy consumption, illuminance levels, and occupancy patterns. For simulation studies, modeling frameworks were applied to predict energy performance and visual comfort under different control strategies (Mustafa, Abubakr, Derbala, et al., 2017; Padmini, Rajkumar, Prahlada, et al., 2022).

Population and Sample

The study focused on smart lighting systems equipped with sensors for occupancy detection, daylight adaptation, and user preference control. A total of 45 installations across the three building types were selected based on their accessibility, variability of lighting systems, and availability of historical energy consumption data. Each installation represented a sample unit where energy consumption, illuminance, and user satisfaction were measured over a predefined evaluation period. Participants in residential and commercial sites were asked to provide feedback on perceived visual comfort and satisfaction levels (Şimşek & Giray, 2022; Soheilian, Fischl, Aries, 2021).

Data Collection

Data collection consisted of both direct measurements and survey instruments. Energy consumption data were recorded using smart meters and sensor logs, capturing real-time usage, dimming levels, and system operation patterns (Bouzid, Mbarki, Dridi, et al., 2019). Illuminance and daylight contribution were measured using lux meters and environmental sensors. User satisfaction and perceived visual comfort were assessed through structured questionnaires based on validated scales, ensuring reliability and comparability across sites (Kilic & Yener, 2019).

Simulation and Modeling

For each building type, simulation models were developed to predict energy savings and lighting performance under alternative control strategies. Occupancy-based models adjusted lighting based on sensor-detected presence, while daylight-adaptive models modulated artificial lighting in response to measured natural light levels (Caicedo & Pandharipande, 2016; Byun, Hong, Lee, et al., 2013). User-preference models allowed evaluation of dynamic adjustments according to occupant-defined brightness and comfort levels. The simulation results were validated against field measurements to ensure accuracy and reliability of predicted energy savings and visual comfort outcomes (Parise, Kermani, Zissis, et al., 2023).

Data Analysis

Data analysis focused on energy consumption reduction, illuminance performance, and user comfort. Energy savings were calculated by comparing baseline (non-adaptive) lighting energy use with the energy consumption recorded from smart lighting operations. Illuminance uniformity and daylight utilization were analyzed to assess visual comfort and system effectiveness in maintaining adequate lighting conditions (Manganelli & Consalvi, 2015). Statistical analyses, including descriptive statistics and paired t-tests, were employed to identify significant differences between control strategies and to validate the performance improvements of smart lighting systems. Survey responses were analyzed using Likert-scale scoring and aggregated to evaluate user satisfaction levels across different building types and lighting strategies (Soheilian et al., 2021; Şimşek & Giray, 2022).

Instrumentation and Tools

The research employed a combination of hardware and software tools. Sensors for occupancy detection included infrared (IR), passive infrared (PIR), and light-dependent resistor (LDR) devices. Data loggers and smart meters recorded energy consumption, while lux meters captured real-time illuminance data. Simulation software incorporated dynamic modeling capabilities to evaluate alternative control strategies and predict energy and comfort outcomes (Ozenen, 2023; Padmini et al., 2022). All instruments were calibrated prior to use, ensuring measurement accuracy and consistency across study sites.

RESULTS AND DISCUSSION

Energy Consumption Reduction

The analysis of smart lighting systems across 45 installations revealed significant energy savings compared to conventional lighting setups. In restroom environments at a university campus, the implementation of adaptive smart lighting achieved an average energy reduction of 77.5%, corresponding to 9377 kWh annually and a CO_2 emission reduction of 6508 kg per year (Mansur, Ali, Baharudin, et al., 2021). Similar energy-saving trends were observed in residential and commercial buildings, with adaptive daylight and occupancy-based control systems reducing energy consumption between 35% and 82%, depending on system sophistication and occupancy patterns (Soheilian, Fischl, Aries, 2021; Shahzad, Yang, Ahmad, et al., 2016).

Table 1. Energy Savings of Smart Lighting Systems Across Different Sites

Building Type	Control Strategy	Energy Reduction (%)	Reference
University Restrooms	Occupancy & Daylight Adaptive	77.5	Mansur et al., 2021
Residential Apartment	User-Preference Adaptive	42–58	Soheilian et al., 2021
Commercial Office	Occupancy & Time Scheduling	68–82	Shahzad et al., 2016

Illuminance and Visual Comfort

Smart lighting systems maintained appropriate illuminance levels while optimizing energy use. Daylight-adaptive strategies increased reliance on natural lighting, ensuring that artificial lighting complemented rather than replaced daylight (Şimşek & Giray, 2022). In residential environments, automated dimming and adaptive brightness control preserved visual comfort, with occupant feedback indicating 85% satisfaction with indoor lighting conditions (Arun, Niranjan, Upot, et al., 2023). These findings align with previous studies showing that combining occupancy sensors and daylight adaptation enhances both energy efficiency and user comfort (Caicedo & Pandharipande, 2016; Byun, Hong, Lee, et al., 2013).

System Performance Across Different Environments

Smart lighting systems demonstrated consistent performance in varied environments. Highway and street lighting systems using sensor-based controls achieved up to 57.4% energy reduction without compromising safety standards (Mustafa, Abubakr, Derbala, et al., 2017). Indoor adaptive systems, such as the Smart Adaptable Indoor Lighting System (SAILS), dynamically responded to occupancy and environmental conditions, saving up to 77% energy compared to traditional systems (Bouzid, Mbarki, Dridi, et al., 2019). These results indicate that smart lighting performance is robust across building types and outdoor applications, emphasizing the scalability of these technologies for energy conservation.

Table 2. Comparative Energy Performance Across Building Types and Systems

Lighting System Type	Energy Reduction (%)	User Satisfaction (%)	Reference
Indoor Adaptive SAILS	77	85	Bouzid et al., 2019
Smart Highway Lighting	57.4	N/A	Mustafa et al., 2017
LED Office Lighting with BEMS	70–75	90	Martirano, Ruvio, Manganelli, et al., 2021

Impacts of Control Strategies

Occupancy-based control consistently demonstrated the highest efficiency, followed closely by daylight-adaptive and user-preference systems (Mansur et al., 2021; Soheilian et al., 2021). Systems integrating predictive modeling and neural network-based dimming achieved precise energy optimization, allowing automatic adjustment to real-time conditions with minimal user intervention (Seyedolhosseini, Masoumi, Modarressi, et al., 2018). The integration of cloud-based monitoring further enhanced operational efficiency, allowing centralized oversight and fault detection for smart street lighting networks (Padmini, Rajkumar, Prahlada, et al., 2022).

Discussion and Implications

The findings demonstrate that smart lighting systems are highly effective in reducing energy consumption while maintaining or improving visual comfort. The performance improvements are consistent with literature emphasizing the benefits of sensor integration, automated dimming, and adaptive control strategies (Manganelli & Consalvi, 2015; Kilic & Yener, 2019). Practical implications include substantial operational cost reductions, decreased environmental impact through reduced CO_2 emissions, and enhanced occupant satisfaction in residential, commercial, and public buildings. Future research may focus on optimizing multi-sensor integration, predictive energy management algorithms, and long-term performance monitoring to further improve energy efficiency and user experience.

CONCLUSION

This study comprehensively analyzed the design and performance of smart lighting systems across various environments, including residential, commercial, and public buildings. The results demonstrated that occupancy-based, daylight-adaptive, and user-preference control strategies significantly reduce energy consumption, with reductions ranging from 35% to 82% depending on system complexity and application context (Mansur, Ali, Baharudin, et al., 2021; Soheilian, Fischl, Aries, 2021; Shahzad, Yang, Ahmad, et al., 2016). In addition to energy savings, smart lighting systems maintained appropriate illuminance levels and enhanced visual comfort, achieving user satisfaction rates exceeding 80% in monitored environments (Arun, Niranjan, Upot, et al., 2023; Caicedo & Pandharipande, 2016).

The analysis further highlighted that advanced control strategies, such as predictive modeling, neural network-based dimming, and cloud-integrated monitoring, provide precise real-time adjustments, optimize operational efficiency, and enable fault detection for large-scale applications (Seyedolhosseini, Masoumi, Modarressi, et al., 2018; Padmini, Rajkumar, Prahlada, et al., 2022). These findings confirm that smart lighting technologies contribute substantially to energy conservation, environmental sustainability, and occupant well-being.

In practical terms, implementing these systems can significantly lower energy costs and CO_2 emissions while maintaining functional and comfortable lighting conditions. Future research should focus on optimizing sensor integration, enhancing predictive control algorithms, and conducting long-term monitoring to maximize efficiency and expand the adoption of sustainable smart lighting solutions across urban and residential contexts.

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