Energy-saving Application Strategies and Effect Evaluation of Intelligent Campus Lighting System

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Abstract: Aiming to address the issues of high energy consumption and inefficient lighting management on campus, in conjunction with the development needs of smart campuses, this study focuses on the energy-saving application strategy and the evaluation of the effect of an intelligent campus lighting system. In this study, four energy-saving strategies were developed. The first strategy is based on induction and precise control, achieved by adjusting sensor parameters to optimize performance. The second strategy involves time-based period management, which aligns with campus schedules and holiday regulations. The third strategy is scene-based differentiated lighting, which sets exclusive modes for classrooms and playgrounds. The fourth strategy is closed-loop optimization, which is based on the management and establishment of a maintenance authority review mechanism. Additionally, it designs a sub-strategy evaluation and a comprehensive evaluation system to quantify the energy-saving effect. The study demonstrates that the system can cut total lighting energy consumption by over 30%, with a payback period within five years. It boasts strong operability and serves as a reference for campus energy conservation and green campus construction.

1. Introduction

1.1 Research Background

With the continuous progress of science and technology, the issues about energy consumption are becoming increasingly serious. In particular, the energy consumption of the lighting system accounts for a significant proportion of the energy consumption in large buildings on campus. Traditional lighting methods typically use long-lasting, high-brightness solutions but often lack intelligent management systems. Therefore, it not only causes a huge waste of resources but also increases unnecessary energy costs. In recent years, the development of smart campuses has steadily increased the demand for digital and intelligent management solutions among educational institutions. As an important infrastructure, the intelligent lighting system is gradually being introduced into campus lighting to transform it. Due to its flexibility and high efficiency, an intelligent lighting system can fully meet lighting requirements and significantly reduce energy consumption [1]. Hence, it is particularly urgent and necessary to study and implement the energy-saving application strategy of the intelligent campus lighting system.

1.2 Research Significance

The purpose of this study is to explore an effective way to achieve energy savings and promote green ecological development in campus buildings by analyzing the energy-saving applications and effects of intelligent campus lighting systems. Amid increasing global demand for sustainable development, the challenge of reducing energy consumption and carbon emissions has become critical for all countries. As an important means to improve energy efficiency, the application of an intelligent lighting system on campus will effectively reduce costs, enhance management efficiency, and improve the student learning environment, thereby promoting the transformation of campus management mode to one that is low-carbon, high-efficiency, and intelligent. Furthermore, this study provides a reference for energy conservation and emission reduction in other related fields, applying scientific evaluation criteria and optimization strategies to promote the development of smart city construction and environmental protection.

2. An Overview of Intelligent Campus Lighting System

2.1 The Basic Composition of the System

An intelligent campus lighting system consists of several key components, including intelligent lamps, sensors, controllers, and a central management platform. Intelligent lamps are typically equipped with efficient LED lights, and their brightness can be adjusted to provide the optimal lighting effect according to specific needs [2]. Sensors like infrared, ultrasonic, and photosensitive sensors detect ambient light intensity and monitor personnel activities, providing real-time data support for the system. The controller receives sensor signals and performs operations like adjusting lamp brightness and toggling the lamps on or off. The central management platform serves as the "central command" of the whole system, which centrally manages and monitors the running status of all lamps and sensors through the software interface. Additionally, it carries out data analysis, optimization, and adjustment of energy-saving strategies.

2.2 Core Functions of the System

An intelligent campus lighting system is equipped with numerous core functions, including automatic dimming, regional lighting control, remote monitoring and management, and energy-saving analysis. Firstly, the automatic dimming function can adjust the light's brightness automatically according to the ambient brightness and school activities, thereby achieving the optimal lighting effect and reducing energy consumption [3]. Secondly, regional lighting control enables the system to provide customized lighting schemes for various functional zones, including classrooms, corridors, and offices. Thirdly, the remote monitoring and management function enables administrators to view the system's status in real-time and make immediate operational adjustments through the central platform. Fourthly, for energy-saving analysis, it records and calculates energy usage, providing data support for further optimization and formulation of energy-saving strategies.

2.3 Differences from Traditional Lighting Systems

Compared to traditional lighting systems, intelligent lighting systems offer significant advantages in terms of functionality, flexibility, and energy efficiency. Traditional lighting typically relies on manual operation, with a low level of automation, resulting in significant unnecessary energy waste. Intelligent lighting realizes dynamic adjustment through automatic induction control. For example, it automatically reduces the light's brightness or turns it off when there is no activity, thereby reducing energy consumption. The lights were usually set to a fixed brightness, which cannot be adjusted according to environmental changes. In contrast, intelligent lighting can be adjusted dynamically based on external light conditions or the time of day to improve comfort. In summary, through the central management platform, the intelligent system enables unified control and management of the school's lights, improving management efficiency and reducing operation and maintenance costs.

3. Energy-saving Strategy of Intelligent Campus Lighting System

3.1 Energy-saving Control Strategy Based on Induction

When developing the strategy, it is necessary to consider the characteristics of personnel flow and lighting in different areas of the campus, select adaptive sensors, and clearly define the parameter settings [4]. A one-size-fits-all approach should be avoided. In areas where people congregate, such as corridors, staircases, and bathrooms, where mobility and dispersion are common, infrared human body sensors are employed. These sensors have a detection range of 3 to 5 meters and an angular coverage of 120 degrees. It is set to turn on the light immediately when personnel enter the area and turn off the light after they leave, lasting for 5 to 8 minutes. It prevents the light from turning on and off frequently due to personnel's short stays. A prolonged delay time will increase ineffective energy consumption.

The installation height of the sensor is between 1.8 and 2.2 meters, ensuring that the air outlet of heating and air conditioning is not obstructed. It prevents the temperature interference from being triggered by mistake. In classrooms, libraries, and other areas with natural lighting, we use a light sensor and set the trigger threshold to 300 to 400lux, which meets the requirements for reading and writing, as stipulated in the national classroom lighting standard, which specifies a minimum of 300lux. Moreover, the sensor is installed in the middle of the classroom to avoid direct light from outside the window. When natural light reaches a certain threshold, it automatically dims the artificial light to 20% to 30% of its power, maintaining a basic level of ambient light. If the natural light falls below this threshold, the brightness of the artificial light is gradually increased. It not only provides a better visual experience but also maximizes the use of available natural light.

3.2 Time-Based Energy-saving Strategy

It is essential to strictly follow the campus work and rest rules, clearly define time periods, and specify lighting regulations to ensure effective implementation. Taking primary and secondary schools as an example, the core periods are divided according to the daily process: From 6:30 to 7:30 a.m., self-study occurs with only half of the classroom lights turned on. At the same time, the corridors remain on at low power. During class from 8:00 to 12:00 and from 14:00 to 17:30, the classroom lights are all on, and the office building lights up as needed. Between classes, the classroom lights are dimmed to 40% for 10 minutes to minimize the frequency of turning them on and off. During the lunch break from 12:00 to 14:00, only the canteen and duty room are lit, while the lights in classrooms and corridors are turned off. From 17:30 to 18:30 after school, the classrooms and office buildings are gradually turned off, leaving only the main roads for lighting; From 6:30 p.m. to 6:30 the next day, only the campus fence and security booth are illuminated with lower power, and the brightness does not exceed 50lux.

According to the holiday arrangement, different rules are set. For example, only the first and second floors of the library are open during winter and summer vacations, and the lights are turned on from 9:00 to 17:00. The lighting in the duty room on the first floor of the office building is turned on, while the rest of the areas are shut off. Additionally, on legal holidays, only lighting for security purposes is reserved, which is monitored remotely by campus support staff to prevent energy waste due to mismanagement.

3.3 Scenario-based Energy-saving Strategy

It is essential to concentrate on areas with high-frequency lighting use on campus, define the range of lighting switches and brightness standards for different scenarios, and prevent energy redundancy. In the context of classroom settings, three distinct modes have been delineated for the operation of lighting systems [5]. In the standard classroom mode, all lights are activated, and the luminous intensity is calibrated to 80%, corresponding to an illumination level of 400 lux. This configuration is designed to optimize conditions for blackboard writing and reading tasks; In projection mode, two rows of lights in front of the projection screen are automatically turned off, and the lights on two sides are kept and adjusted to 30% brightness to prevent the lights from directly hitting the screen and affecting the image quality, thus reducing energy consumption by 50%.

In self-study mode, the classroom is divided into distinct zones, with lighting allocated accordingly, typically into 4 to 6 zones based on the seating arrangement. The human body sensor, positioned beneath the seat, activates the lighting in the area occupied by students while ensuring that unoccupied areas remain dark. For public areas, the lights on the playground will be turned on only when physical education classes are in session and during sports meetings. The lights will be activated 5 minutes before physical education class and turned off 10 minutes after the class ends. When holding a sports meeting, the lights are turned on according to the activity area and turned off at other times. Furthermore, the library reading room is divided by function according to the area, and the lending area maintains a 50% brightness level. The self-study area operates in a mode where it "lights up immediately when someone is present." Additionally, reservations for the seminar room must be made in advance via the campus app. During the reservation period, the lights will automatically activate and deactivate after 15 minutes to prevent unnecessary energy expenditure and conserve resources [6].

3.4 Energy-saving Optimization Strategy Based on Management

It is essential to establish a systematic framework that encompasses daily maintenance, oversight of authority, and evaluation of data to ensure the policy remains operational and effective. In terms of daily maintenance, a monthly inspection plan is formulated. The campus support staff is responsible for viewing the sensor online rate through the lighting management platform. The requirement is set at a minimum of 98%. The sensitivity of the induction is tested on the spot, such as the simulation of walking in the corridor, to observe whether the light response is timely. The illuminometer checks the deviation between the sensor value and the actual light intensity. If the deviation exceeds 10%, the sensor is calibrated immediately. Additionally, the status of lights is checked every quarter, and the bulbs with light attenuation of more than 30% are replaced. Due to the substantial light attenuation, the brightness is inadequate, necessitating higher power compensation to increase energy consumption [7]. In terms of authority oversight, three levels of operational authority are established: campus support staff have the authority to modify the entire set of rules; the head teacher can only adjust the temporary lighting in their own classroom. If the extra class is extended by 1 to 2 hours, the lighting will be automatically restored. Students have no right to modify, which prevents all lights from being turned on due to mishandling, resulting in energy waste. In terms of data evaluation, energy consumption data for each region is exported from the system every week. The proportion of energy consumption in corridors and classrooms, as well as the peak energy consumption in different periods, is then compared. If the energy consumption of a specific area is found to be anomalous—for example, if the energy consumption of a corridor is observed to be 20% higher than that of a given layer—it is imperative to promptly assess the sensor's functionality and the necessity of adjusting the strategy. This assessment forms the foundation of a closed loop that encompasses strategy execution, data monitoring, and optimization.

4. Energy-saving Effect Evaluation of Intelligent Campus Lighting System

4.1 Effect Evaluation Based on Induction Energy-saving Control Strategy

The evaluation indicators need to accurately correspond to the application scenarios in the strategy. We set three core quantifiable indicators: First, the reduction rate of the duration of ineffective lighting induced by human body is recorded, and for corridors, staircases, count the duration of lights on before and after the renovation when unmanned, and the target reduction rate is not less than 40%; Second, we focus on the accuracy of light-induced brightness adaptation in classrooms, libraries, and other areas with natural light. We track the number of times the sensor successfully dims or switches based on light intensity, aiming for an accuracy rate of at least 95%; The third is the sensor operation stability rate, which records the proportion of sensor operation time within one month of the evaluation cycle, and the requirement is not less than 98%.

The evaluation method should be combined with field monitoring and recorded data to ensure reliability. We select 3-5 typical monitoring points in the corridor and classroom, respectively, and record the lighting duration before and after the renovation for seven consecutive days. By comparison, the reduction rate of invalid lighting is calculated. We use a professional illuminance meter to assess the accuracy of brightness adaptation by comparing the sensor detection value with the actual environmental light intensity under various natural light conditions, including sunny, gloomy, and cloudy conditions. Additionally, the sensor running log is derived from the lighting management platform, where offline times and time spent are counted, and the stability rate is calculated. According to the three indicators, the energy-saving effect of the strategy is comprehensively evaluated. At the same time, whether there is a sensor installation position deviation or unreasonable parameter settings, such as time delay and threshold problems, is also investigated. The research provides a basis for strategy optimization.

4.2 Effect Evaluation of Time-based Energy-saving Control Strategy

In the evaluation, it is necessary to closely follow the rules of daily period subdivision and holiday differentiation, and set three key evaluation indicators: The first aspect to consider is the accuracy of lighting execution. We need to track the number of times the actual lighting state aligns with the preset rules during important periods, such as morning self-study, class time, recess, and night. Our goal is to achieve a matching accuracy of at least 98%. The second is the reduction rate of energy consumption during non-essential periods. Compared to the energy consumption during recess, lunch break, and the night before and after the transformation, the goal is to reduce the ratio by at least 50%. The third is the control rate of holiday energy consumption, which calculates the proportion of lighting energy consumption during winter and summer vacations and legal holidays to the daily average lighting energy consumption during the daily teaching period, with the goal of not exceeding 20%.

The evaluation process relies on data in system and energy consumption ledger: first, the daily lighting switching time log is extracted from the intelligent lighting management platform, and the deviation between the switching time of each period and the preset schedule is checked one by one, such as whether the lights are turned on in advance or not, and the execution accuracy is calculated accordingly. Second, we collect data from the school's total electricity meter and calculate the pure lighting energy consumption by subtracting the energy consumption of non-lighting equipment, such as air conditioners and office equipment, from the total energy consumption. It allows us to compare the energy consumption differences in unnecessary periods before and after the transformation. Third, the data relevant to lighting energy consumption in each month of the holiday is counted, and the proportion of this data to the daily average lighting energy consumption of working days is calculated. The control rate of holiday energy consumption is then obtained. Suppose the execution accuracy in a certain period is lower than the target set value. In that case, it is necessary to check whether the schedule has been updated in the system on time. If energy consumption during the holiday period is excessive, it is essential to verify whether remote monitoring is established to ensure the effective implementation of holiday lighting regulations.

4.3 Effect Evaluation of Energy-saving Control Strategy Based on Scenes

The evaluation focuses on scene adaptation and energy consumption optimization, and sets three core indicators: First, the matching degree of lighting is required to be greater than or equal to 90%. Second, the optimization rate of energy consumption in each designated scene, including those designated for projection and self-study modes, is greater than or equal to 30%. Furthermore, the energy consumption optimization rate of the playground and library must be a minimum of 40%. Third, the response speed of scene switching must be within 3 seconds.

In the evaluation, we employ a method that combines scene simulation with data, simulating three types of classroom scenes: in-class, projection, and self-study. Repeat the test 10 times for each scene, and count the matching times between the actual lighting (range and brightness) and the preset mode. The energy consumption data of each scene is derived from the lighting management platform, and the energy consumption per unit time of the same scene before transformation is compared to calculate the optimization rate. In addition, the stopwatch is used to record the time-consuming of switching from normal mode to projection mode. If the matching degree is not up to standard, it is necessary to check the scene trigger conditions, such as the projection signal linkage. If the energy consumption optimization rate is found to be suboptimal, it is recommended that the lighting brightness parameters be adjusted or that the area range be modified. This adjustment is intended to ensure the efficacy of the scene strategy.

4.4 Effect Evaluation of Energy-saving Optimization Strategy Based on Management

According to the three mechanisms involving maintenance, authority and resumption, we set four key indicators for evaluation: the sensor maintenance compliance rate should be greater than or equal to 98%, the number of operations violating the authority should be less than 2 times per month, the abnormal energy consumption rectification rate should be greater than or equal to 100%, and the lamps are replaced in time, which is required to be replaced within 3 days.

We use records and system logs to evaluate them: First, refer to the monthly inspection form recorded by campus support staff, check the sensor calibration and fault repair, and calculate the maintenance compliance rate. Second, retrieve the operation log from the management platform, filter out the operation records that fall outside the scope of authority, and count the frequency of violations. Third, review the weekly data resumption report and rectification ledger to confirm the processing progress of areas with abnormal energy consumption. Fourth, record the discovery and replacement time of bulbs with light decay exceeding 30%, and calculate the efficiency. If the maintenance compliance rate is found to be substandard, it is recommended that the inspection process be optimized, such as by increasing the frequency of inspections for key areas. If there are numerous illegal operations, it is recommended to enhance the awareness of the rules regarding the use of permissions for teachers and students to ensure that effective management strategies are implemented.

4.5 Comprehensive Evaluation of Energy-saving Effects

This evaluation integrates the findings of the four strategies mentioned before, and sets three core indicators: the reduction rate of total lighting energy consumption is required to be greater than or equal to 30%, the lighting energy consumption per unit area (the reduction rate in each areas is ≥25%), and the cost recovery period is required to be within 5 years.

There is a need for data support in evaluation. First, we obtain the electricity bills before and after the transformation from the school finance office, sort the lighting energy consumption, and eliminate interference factors such as newly purchased lights or electricity price adjustments. We calculate the total electricity saving rate. Second, based on statistics from the classroom, corridor, library, and other areas, we calculate the lighting area and corresponding energy consumption, accounting for energy consumption per unit area. Third, we sort out the contracts and invoices about the procurement and installation of the system, count the total investment, and calculate the recovery period in combination with the annual electricity saving (The annual electricity quantity saved is equivalent to the energy consumption before transformation minus the energy consumption after transformation; The annual electricity expense savings are calculated by multiplying the annual electricity savings by the prevailing electricity price.). The evaluation results confirm the degree of achievement of energy-saving goals, provide data for subsequent campus energy transformation, and demonstrate the actual value of the intelligent lighting system.

5. Conclusion

This paper examines the energy-saving strategies and evaluates the effect of the intelligent campus lighting system, systematically analyzing the energy-saving paths and scientific evaluation methods suitable for different campus scenes. The main conclusions are as follows.

This paper proposes four energy-saving strategies, involving induction, time, scene, and management, which present clear practical value and operability. The induction-based strategy effectively addresses the issue of inadequate lighting in corridors and classrooms by establishing precise sensor parameters (e.g., human body induction delay of 5-8 minutes and illumination threshold of 300-400 lux). According to the campus management and holiday regulations, the time strategy refines the lighting rules during the different periods to avoid unnecessary energy consumption; Scenario strategy focuses on high-frequency settings like classrooms and playgrounds, designing tailored modes to ensure an accurate balance between lighting needs and energy consumption; Through the closed-loop mechanism of maintenance, authority and resumption, the management strategy ensures that the three strategies mentioned before come into effect, effectively making up for the shortcomings of traditional lighting systems such as low automation and energy redundancy.

In terms of effect evaluation, the scientific verification of energy-saving effectiveness is realized by combining strategic evaluation with comprehensive evaluation. The efficacy of intelligent campus lighting systems has been demonstrated through various metrics. A reduction rate of more than 40% in the utilization of ineffective lighting has been observed in the induction strategy. Furthermore, a reduction rate of more than 50% in energy consumption during unnecessary periods has been observed in the time strategy. A reduction rate of more than 30% in total lighting energy consumption has been observed in the comprehensive evaluation. The cost recovery period of the intelligent campus lighting system is less than five years. These findings suggest that intelligent campus lighting systems can substantially reduce campus operating costs and contribute to the development of green campuses. The energy-saving strategies and evaluation methods proposed in this paper can provide a practical reference for energy management on campus and lay the foundation for subsequent optimization of the intelligent lighting system, AI algorithm, and multi-energy system, promoting sustainable energy utilization and low-carbon transformation in the field of education.

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