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An energy efficient approach to minimize energy consumption for exterior lighting in Egypt

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Lighting systems, Energy efficiency, smart lighting, landscape lighting, Façade Lighting, sustainability, Egypt.

Abstract: Lighting systems are crucial in enhancing architectural aesthetics while promoting energy efficiency in both building facades and outdoor areas, particularly in regions with high energy demands like Egypt. This research examines the applicability of different lighting solutions like LED lighting systems, intelligent "IoT-based" lighting systems, and solar-integrated lighting in the Egyptian context. The study compares each system's performance, cost-effectiveness, and compatibility with architectural needs. LED lighting, with its high energy efficiency and adaptability to various architectural designs, emerges as a practical choice due to its low energy consumption comparable to other building loads, especially when integrated with intelligent lighting control systems, which utilize IoT and sensor-based controls, aligning with Egypt's smart city initiatives and offering significant energy savings by adapting to real-time environmental conditions. Solar-integrated lighting, though promising as a renewable solution, faces challenges in dense urban settings due to spatial constraints and higher initial costs. The analysis concludes that Solar powered LED and intelligent lighting systems are the most applicable technologies for lighting in Egypt, supporting sustainability and urban development goals. Future research can work on the application framework and guidelines that can be used as a reference for efficient lighting design in Egypt.

1. Introduction

One of the main issues harming humanity today is global warming. Greenhouse gas emissions from the burning of fossil fuels are one of the primary drivers of global warming. Reducing greenhouse gas emissions requires raising energy production from renewable sources and making efficient use of the energy generated for the planet's future. The majority of our society's energy use is found in built environments. It ultimately means that due to the building environment's impact, high attention should be turned to energy consumption. Lighting is a key aspect of the built environment that consumes a significant amount of energy. Several countries have established various kinds of measures aimed at reducing greenhouse gas emissions, such as lighting and energy efficiency [1,2]. These measures seek to reduce electricity consumption, eliminate light pollution, and promote sustainable urban spaces to achieve Koyoto Protocol [3] and the Paris Agreement signed in 2015 [4] as according to a report from the International Energy Agency (IEA), energy use for lighting

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purposes is connected with around 19% of the total electricity produced in the world [5]. Outdoor lighting in urban and rural environments consists of various components, each of which contributes to the overall appearance of the city or area. There are two kinds of lighting; i) functional lighting that is required for the function of the areas, such as lighting of walkways, roads, underground passages, parking areas, etc. and ii) Architectural or aesthetic lighting that emphasizes key characteristics, like illuminating facades, landscapes, urban sculptures, and other architectural components [6]. Both approaches are necessary to have a holistic urban or rural lighting image, so as life continues after sundown.

Landscape and street lighting are samples of functional lighting. It is responsible for both driver's and pedestrians' safety, their visual perception and accident avoidance especially with pedestrian victims [7,8]. However, there are some aspects that should be considered when designing the building envelope, as the building's facade lighting is added to the urban lighting which aims to promote nightlife and to facilitate several activities that are implemented at night in outdoor spaces. Architectural concepts remain a priority. In this context, aesthetic appearance and visual comfort become crucial. An architectural building and its surroundings can interact through the use of facade illumination. The visual impact exerted by a building during the evening and night represents its urban presence, and today, the increasing number of pedestrian areas fosters the night attractiveness of buildings [9]. Therefore, by considering the location, the building's perspective, and the visual effect from various viewing angles, outdoors façade lighting has a significant impact on the viewer's perception [10,11]. Design process, well known in architecture, covers all actions (not only strategy selection) that lead to the final solution appropriate in terms of quantity and quality of the illuminated object, lighting conditions, energy efficiency, maintenance costs, and influence on the natural environment are made. The design team is responsible for the lighting results, correct system functioning and the costs involved.

Optimization of the facade for a reduced demand for building services may well achieve a level of energy efficiency [12]. Attention should be also given to the right choice of façade lighting techniques in order to highlight building's volume and structure and to avoid at the same time high levels of light pollution [13]. To achieve this goal, effective facade lighting strategies that integrate technology and design for low energy consumption, leveraging advancements in LED lighting (Light-Emitting Diodes), automated lighting controls, and sustainable design approaches such as solar integrated lighting, must be considered. Many recent studies have investigated energy efficiency and user comfort within smart LED systems in different scenarios. It's proved that LED is very low energy consumption in comparison to other building loads [14]. They assessed smart LED systems with optimum dimming function, capable of adjusting optical LED output power, with the goal of achieving maximum energy savings while meeting users' comfort at the same time [15,16,17].

Traditional lamp control techniques like manual, induction, and timed control lack intelligence and cannot satisfy the demands of current urban construction. With the rapid growth of communication and microelectronics technology, intelligent lighting systems with Internet of Things have gradually emerged as the most promising research field, such as using wireless network technology to monitor lamp status and detect traffic flow and environment [18,19]. This study explores current trends in efficient exterior lighting systems to identify small but significant interventions aimed at reducing energy consumption in the urban environment, primarily in Egypt, and particularly in urban landscape and façade lighting. This goal will be achieved by comparing several systems to determine which ones are the most efficient and appropriate for the Egyptian context.

2. Methods and tools

This study's methodology consists of three key components: a literature survey, data analysis, and a comparative assessment of systems.

1. **Literature Survey:**
   A detailed review of existing research, theories, and frameworks is carried out to establish a strong basis for the study. This involves reviewing academic publications, industry reports, along with relevant case studies to identify current trends, difficulties, and gaps in this area of study.
2. **Data Analysis:**
   The study employs quantitative data analysis techniques to process and interpret collected data. Systems comparison was used to identify significant insights that contribute to the research objectives.
3. **Comparison between Systems:**
   To reach the study's goal, a comparative analysis is conducted on several systems. This includes evaluating several characteristics, including performance, efficiency, cost-effectiveness, and dependability. The comparison helps to discover strengths, challenges, and the ideal application for each system.

By combining these three methodological techniques, the research ensures an extensive review of the topic, leading to solid conclusions and suggestions.

3. Review of available lighting systems

This section examines several façade and landscape lighting systems to determine their energy efficiency and low-energy consumption properties. LEDs, solar-integrated lighting, and intelligent lighting control systems have been explored for their efficiency, the lifespan, and cost-effectiveness as follows:

3.1. LED Lighting Systems

Selecting the appropriate bulb is critical for an energy-efficient lighting system. In recent years, various studies have investigated the use of LED lighting (Light-Emitting Diodes) instead of old traditional bulbs to reduce operational electricity consumption and so contribute to energy efficiency [15,20,21]. Such interventions abroad have shown that with only the replacement of lamps with LEDs, energy savings more than 50% can be achieved. However, when the most recent management systems are used, the savings achieved can exceed 70% [22,23]. A recent case study of Priboj municipality replaced existing lighting “2530 light bulbs” with LED lighting and compared the electricity consumption for four months of 2019 and the same four months of 2020. It showed that electricity consumption for these four months was reduced by an average of 55% [24]. Nevertheless, the replacement of the lamps is not sufficient, and thus, additional measures need to be taken. Furthermore, advancements in LED technology have enabled manufacturers to design customizable and dimmable lighting systems that reduce energy use further by adapting light levels based on ambient conditions. Many recent studies investigated energy efficiency and user comfort within smart LED systems in various scenarios. More specifically, studies [17, 25-29] investigated smart LED systems with optimal dimming features capable of adjusting optical LED output power in order to achieve maximum energy savings while also meeting user comfort.

Nevertheless, the mere fact of using LED technology does not always guarantee the best possible solution [31]. As despite their advantages, such as economic growth, reduced public spending, lower energy consumption, and decreased pollution, LEDs have drawbacks. These include heat dissipation, blue light hazards, limited lifespan, and the adverse effect on the electrical power system (harmonic generation) [31]. These challenges have encouraged the development of more sustainable solutions like solar-integrated lighting and IoT-based systems.

3.2. Solar-powered LED Lighting

The demand for energy is growing as a result of population growth, technological advancements, and the expansion of electrical appliances. If this problem continues, we will face a fuel problem for electricity generation in the near future. Many researchers have proposed the usage of renewable energy as an effective way for handling this issue. Solar energy, which is one type of renewable energy, is considered one of the most popular types of renewable energy due to its easy access. Power electronic converters are one of the main components of these renewable energy systems. Given that solar systems produce DC electricity, DC/AC converters play a crucial role in photovoltaic system structure [32,33]. An example of this solar powered LED system structure is shown in Fig. 1.

Solar-powered LED (light-emitting diode) lighting systems depend on photovoltaic panels to generate electricity from sunlight, which is stored in batteries and used to power LED lights. These systems provide substantial energy savings, reduce dependence on the national grid, and eliminate greenhouse gas emissions. This energy has applications on both large and small scales, including solar power plants and street, façade, and urban landscape lighting [34]. Statistics show that PV-powered LED streetlights are widely used in a variety of applications all over the world [35].

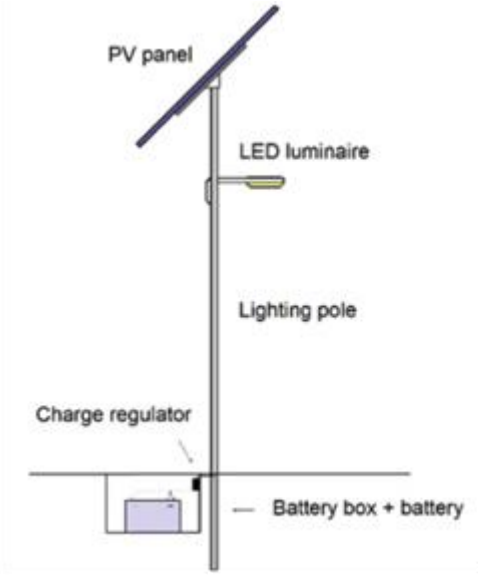

Fig. 1: Solar powered LED system example [34]

3.3. Intelligent "IoT-based" Smart Lighting Systems

A smart city leveraging IoT technology requires an intelligent lighting system for effective management [36]. A Smart Lighting System (SLS) is an automated control lighting system deployable across multiple locations, utilizing IoT protocols, devices, and sensors. SLS aims to optimize energy use by efficiently managing lighting, helping to cut down on wasted power in a smart city.

IoT-enabled SLS consists of three layers: perception (sensors), communication, and organization [37]. Its parameters as shown in the example of Fig. 2 [38] can be classified as:

- Sensors detect different factors like Motion detection, light intensity, Environmental detectors like Temperature and Humidity.
- Communication Protocols such as LoRa (Long Range).
- Actuators: LED dimming, Relay response time.
- Control System: Cloud server for Real-time data analysis

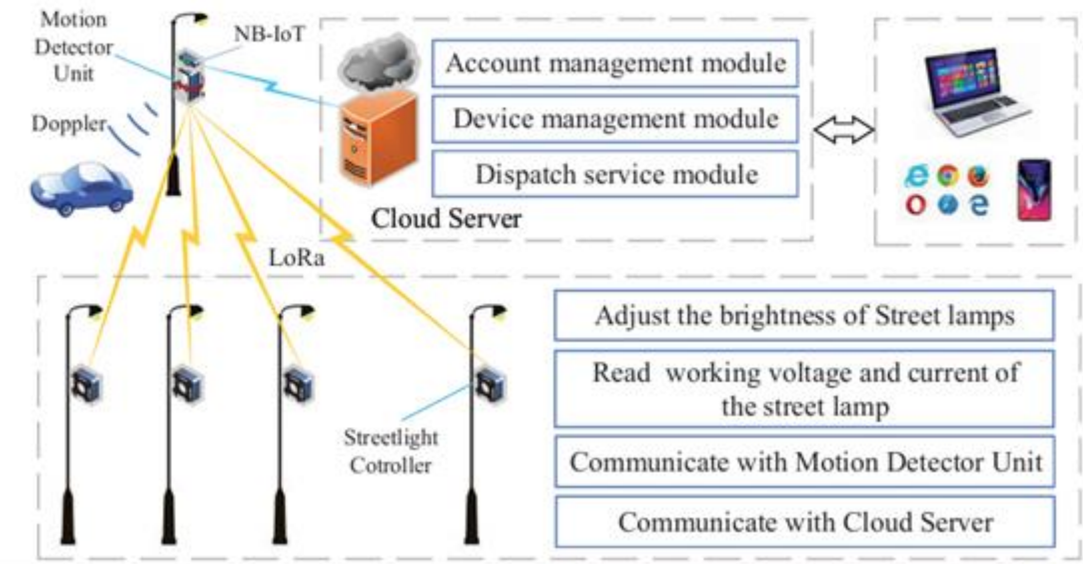

Fig. 2: IoT Smart Lighting system example [38]

Intelligent controls, such as sensors and IoT-based systems, enable real-time monitoring and adaptive adjustments to lighting intensity and duration. By automating dimming and scheduling based on human presence or natural light, these systems significantly cut energy use [39,40].

3.4. Motion-Sensor Lighting

Motion-sensor landscape lighting integrates advanced technology to enhance energy efficiency and safety in outdoor environments. It is a type of Smart Lighting Systems, ideal for reducing energy waste in low-traffic areas such as alleys, footpaths, and gardens. These systems activate lighting only when movement is detected, significantly reducing energy waste during off-peak hours. This approach improves user experience and supports sustainable urban development. While cost-effective and easy to implement, they may require periodic recalibration for maintaining their accuracy [41].

Concerning Energy Efficiency:

- Motion sensor lights, especially those with Passive Infrared (PIR) sensors, activate only when a movement is detected, minimizing power use as shown as an example in **Error! Reference source not found.** [41].
- Environmental sensors in smart streetlights enable adaptive lighting based on real-time conditions, further optimizing energy consumption [42].

Concerning Smart Technology Integration:

- Modern motion-sensor lighting fixtures often include wireless transceivers, allowing networked coordination of lighting based on detected movement [43].
- These systems can also collect environmental data, proving their functionality in addition to illumination [42].

And for the User-Friendly Design:

- Many motion sensor lights are designed for easy modification, enabling users to convert standard LED lights into motion-activated fixtures with simple tools [41].
- Features like delay settings in motion sensor bulbs offer customizable lighting solutions [44].

While motion-sensor landscape lighting provides many benefits, reliance on technology can lead to potential malfunctions or maintenance challenges, which could disrupt its energy-saving advantages.

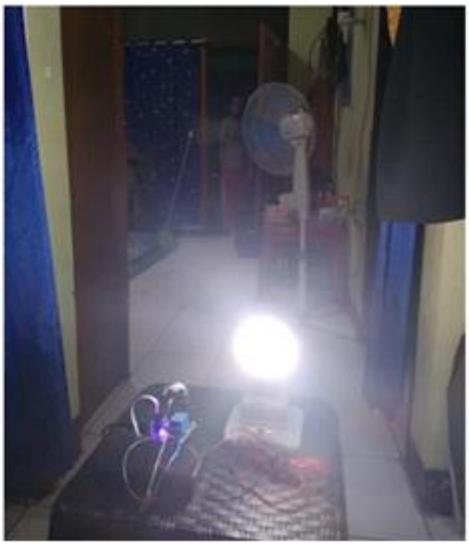

Fig. 3: Example of sensor detects motion at a distance of 5 meters [41]

4. Comparison between lighting systems

To determine the most suitable lighting solutions for Egypt, a comparative analysis is provided in **Error! Reference source not found.**, considering energy efficiency, cost, maintenance, and the ideal application ⁄location that each system can be used in.

Table 1: Comparison between lighting systems

Lighting System	Components	Benefits	Challenges	Energy Savings	Ideal Applications
LED Lighting Systems	- LED light fixtures - Drivers and transformers - Dimmers - Heat sinks - Smart controls (optional)	- High energy efficiency [23,25]. - Long lifespan, reducing maintenance needs and costs. - Customizable and dimmable for adaptive lighting (optional).	- Higher initial cost compared to traditional lighting systems. - Limited recycling options, creating waste challenges.	- 50% less than traditional lighting systems [22,23]. - 70% less in case of smart LED [25,24].	- Façade - Landscape
Solar-powered LED Lighting	- Photovoltaic (PV) panels - Batteries for energy storage - Solar-powered LED fixtures Inverters (if connected to grid)	- Use renewable energy, reducing dependence on grid power. - Self-sustaining in suitable climates, especially in sunny regions.	- High initial installation cost - Battery lifespan limitations - Performance dependent on sunlight availability [34,46].	- Up to 30% compared to conventional systems [45].	- Façade - Landscape

Lighting System	Components	Benefits	Challenges	Energy Savings	Ideal Applications
Intelligent "IoT-based" Lighting Systems	- IoT sensors - Control systems - LED luminaires - communication networks	- Real-time energy optimization [39]. - Remote monitoring and control [40]. - Customizable lighting levels.	- Requires complex infrastructure - High maintenance costs [41]. - Potential cybersecurity risks.	- Demonstrated an energy efficiency up to 42.67% [47].	- Façade - Landscape
Motion-Sensor Lighting	- PIR sensors - LED fixtures - control units	- Activates only when needed. - Cost-effective and easy to install [41]. - Reduces light pollution	- High maintenance needed [43]. - Limited coverage range [41].	- Can save energy Up to 70% [41].	- Landscape

5. Results

To assess the weaknesses and potentials that exist, in addition to the measures that must be taken in the near future to reduce energy consumption for outdoor lighting systems in Egypt, a) a review of current norms and b) a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was carried out. The existing norms are initially shown, followed by a SWOT analysis follows so as to find the opportunities and identify the threats in order to avoid them. The **Error! Reference source not found.** shows these norms and the SWOT analysis.

Table 2: Key steps and SWOT analysis

Key Steps	Details
Adapting Local Norms and Applying International Technical Standards	- Existing Norms: - Egyptian Code for Energy Efficiency in Buildings "for residential and commercial buildings". - The Egyptian code for Green, environmentally friendly buildings. - The Egyptian Smart cities code – Part 1 & 2. - The Egyptian Code for the Foundations and Requirements for Planning, Management, Operation and Sustainability of Smart Cities. - The Guide to the design of green hospitals and health facilities - Green Hospital Rating System.
SWOT Analysis in Actions to Minimize Exterior Lighting's Energy Consumption	
Strengths	- Availability of solar energy resources to integrate with lighting systems. - Existing research on energy-efficient lighting in Egypt.
Weaknesses	- Some regions have limited enforcement of lighting standards. - Gaps in technical skills for maintenance of advanced systems. - Large-scale application of sustainable lighting systems is hindered by high initial investment costs, despite their long-term benefits. - Infrastructure limitations: Smart lighting integration requires digital connectivity and stable electricity, which may not be available in all places.

Key Steps	Details
	- Raising public awareness about the benefits of sustainable lighting is crucial for encouraging adoption.
Opportunities	- Potential for public-private collaborations in smart lighting projects. - Energy savings have a significant influence on achieving urban sustainability goals. - Utilizing the country's abundant solar energy resources can lessen the need for fossil fuels. - Government initiatives, such as energy efficiency programs and smart city projects, promote sustainable lighting practices. - Advancements in LEDs and smart systems have made sustainable lighting more affordable.
Threats	- Municipal budget restrictions. - Imported lighting products may be of low quality and non-compliant.
Proposals – Actions – Conclusions	- Conduct pilot projects for solar-integrated smart lighting in urban and rural areas. - Establish training programs for technicians on energy-efficient lighting. - Implement monitoring mechanisms to guarantee compliance with energy-saving objectives. - Develop global partnerships for technological and financial transfer.

6. Discussion

Creating a pleasant urban environment requires a balance between the needs and desires of the client and/or designer, as well as an integration of aesthetics, function, and efficiency. Urban lighting has to be associated with people's preferences. The identical urban lighting network should include both façade and landscape lights. Lighting needs to support performance, health, and well-being. Nowadays, when the environment is in danger, lighting designers should use more energy-efficient lighting solutions to help reduce carbon dioxide emissions from human activity and, more generally, mitigate the effects of climate change [48,49]. Individuals and government both must recognize the issues and respond appropriately. Lighting norms has to be followed when designing exterior lighting even if aesthetic lighting is required. It is certain that private people (i.e., private structures) will adhere to the regulations if the government do. Last but not least, the designers should follow the norms and avoid designing over-sized lighting installations.

The energy efficiency, durability, and affordability of LED lighting systems make them ideal for outdoor illumination in Egypt. In Egypt's hot environment, LED systems can function well because of their heat-resistant components, which include efficient drivers and heat sinks, which lower heat emissions and increase the lighting system's lifespan. LED lighting can be customized to emit only the necessary light, thereby reducing light pollution and enhancing visual comfort in the urban areas [30,31]. This adaptability is valuable in areas where lighting aesthetics are as crucial as functionality.

And while solar-integrated lighting can be effective in low-density outdoor areas or rural developments, its efficiency is contingent on stable sunlight conditions, which may not be fully reliable for façade lighting. Egypt enjoys abundant sunlight, which is advantageous for solar power; however, solar-integrated facade lighting can be restricted by space and design constraints. Solar panels often require substantial surface area, which may not be feasible for all building facades, particularly in dense urban areas where vertical facades are common. Therefore, while solar-integrated lighting remains a promising sustainable solution, it is currently less applicable than LED and intelligent lighting systems in most of Egypt's urban and densely populated areas. Additionally, the initial costs associated with photovoltaic panels and energy storage systems may become a financial barrier for widespread adoption, particularly in areas with budget constraints.

Intelligent lighting control systems also hold strong potential in Egypt due to their capability for adaptive lighting adjustments. By incorporating sensors and IoT-based controls, these systems can automatically reduce lighting intensity during periods of low activity, thus saving energy. Given Egypt's increasing focus on smart city initiatives, especially with projects like the New Administrative Capital, integrating IoT-based lighting systems aligns with the country's vision of modern, sustainable urban development. Intelligent lighting systems can decrease energy usage by up to 42.67%, making them well-suited for large urban development's where lighting demands fluctuate based on occupancy and natural light availability.

In Egypt's climate, which has significant solar exposure, the use of daylight sensors within intelligent lighting systems allows buildings to maximize natural light during the day, reducing the need for artificial lighting. Additionally, motion sensors can ensure that lighting in public spaces is active only when needed, further enhancing energy savings. This flexibility is ideal for mixed-use buildings and residential complexes that are becoming more common in Egypt's urban landscapes.

Energy-efficient, aesthetically pleasing, and environmentally friendly public areas require sustainable urban landscape lighting. The investigation suggests that solar-integrated LED lighting and intelligent lighting control systems are the best options for Egypt because of their affordability and climate-adaptability. And to promote widespread adoption, policymakers should:

- Encourage investment in sustainable lighting technologies.
- Establish pilot projects to assess feasibility in diverse urban settings.
- Develop public-private partnerships to finance large-scale projects.

By adopting these strategies, Egypt can reduce carbon emissions, save a substantial amount of energy, and enhance the quality of its urban landscapes.

7. Conclusions

Modern architectural design relies heavily on energy-efficient lighting systems since they lower energy usage and improve occupant comfort. The technical developments, energy efficiency, and implementation issues of several advanced lighting solutions were examined in this research, including motion-sensor lighting, solar-integrated lighting, smart LED lighting systems, and intelligent lighting control systems. High efficiency and versatility are provided by smart LEDs, while solar-integrated lighting uses renewable energy to reduce reliance on power even more. Intelligent lighting control systems enhance automation and energy savings through IoT and AI-based optimizations, whereas motion-sensor lighting contributes to demand-driven efficiency in residential and commercial spaces.

Nevertheless, these benefits, issues including high initial expenses, complex integration, and system dependability need to be resolved in order to maximize the implementation of these technologies. To enable wider use, future research should concentrate on enhancing AI-driven automation, increasing sensor accuracy, and creating more affordable solutions. Energy-efficient lighting will continue to be a key component of intelligent and sustainable architecture design with further innovation, supporting international energy conservation initiatives.

Egypt's existing infrastructure, particularly its outdoor lighting, presents several challenges for both installation and development. Uneven lighting, excessive or insufficient illumination, and extreme variations on the surface might arise from installing road luminaires without conducting an adequate investigation. Uneven illumination levels are also caused by the lighting poles' different heights or distances from one another. In addition to using luminaires that do not meet the requirements for lowering light pollution, the use of outdated technology luminaires, which use high-pressure sodium and high-pressure mercury lamps with magnetic ballasts, consumes a lot of energy and doesn't meet the specifications. One solution to reduce energy consumption and light pollution is through using efficient fixtures and systems. Solar powered LED lighting and intelligent lighting control systems play a vital role in helping to transform towards more sustainable future for lighting in Egypt as investigated.

Declaration of conflicting interest

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نهج موفر للطاقة لتقليل استهلاك الطاقة في الإضاءة الخارجية في مصر

الملخص

تعتبر أنظمة الإضاءة عنصرًا أساسيًا في تعزيز الجماليات المعمارية مع تعزيز كفاءة الطاقة في واجهات المباني والمناطق الخارجية، خاصة في المناطق ذات الطلب المرتفع على الطاقة مثل مصر. تبحث هذه الدراسة في مدى قابلية تطبيق حلول إضاءة مختلفة مثل أنظمة الإضاءة ذات الصمامات الثنائية، وأنظمة التحكم الذكية في الإضاءة، والإضاءة المدمجة بالطاقة الشمسية في السياق المصري. تقارن الدراسة أداء كل نظام وفعاليته من حيث التكلفة وتوافقه مع الاحتياجات المعمارية. تبرز إضاءة ذات الصمامات الثنائية ، بكفاءتها العالية في استهلاك الطاقة وقدرتها على التكيف مع التصاميم المعمارية المختلفة، كخيار عملي، خاصة عند دمجها مع أنظمة التحكم الذكية في الإضاءة التي تستخدم تقنيات إنترنت الأشياء والتحكم القائم على المستشعرات، مما يتوافق مع مبادرات المدن الذكية في مصر ويوفر توفيرًا كبيرًا في الطاقة من خلال التكيف مع الظروف البيئية في الوقت الفعلي. وعلى الرغم من أن الإضاءة المدمجة بالطاقة الشمسية تعد حلاً واعدًا كمصدر للطاقة المتجددة، إلا أنها تواجه تحديات في المناطق الحضرية الكثيفة بسبب القيود المكانية والتكاليف الأولية الأعلى.

تستنتج الدراسة أن أنظمة الإضاءة العاملة بالطاقة الشمسية والأنظمة الذكية للتحكم في الإضاءة هي التقنيات الأكثر ملاءمة للإضاءة في مصر، لدعم أهداف الاستدامة والتنمية الحضرية. يمكن أن تركز الأبحاث المستقبلية على إطار تطبيق وإرشادات يمكن استخدامها كمرجع لتصميم إضاءة فعالة في مصر.