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Innovative Light Pipe with Integrated Solar Panels

Muhammad Naufal Hakimi Hamdan[1], Ahmad Zaim Zharfan Mohd Azizul Fahmi[1], Muhammad Harith Abd Rahman[1], Aslila Abd Kadir[1,2]*

[1] *Department of Civil Engineering, Centre for Diploma Studies*
Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Johor, MALAYSIA
[2] *Spatial Technology for Civil Engineering (STforCE), Centre for Diploma Studies*
Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, 84600 Pagoh, Johor, MALAYSIA

*Corresponding Author: aslila@uthm.edu.my
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Abstract

Light Pipe System (LPS) are simple system designed to transmit natural light into building interior. They offer a practical solution for illuminating windowless areas. However, their performance is highly dependent on solar attitude due to the small inlet aperture. This study aims to explore a light pipe system integrated with solar panels and LED lights to illuminate indoor area. A 1:10 model of windowless room was tested at UTHM Pagoh, measuring illuminance over 5 days of sunny weather. The result showed that of up to 60% reduction in artificial lighting with more than 100 lux maintained even in dim conditions. The integration can also reduce electricity consumption. It is estimated that approximately RM 59.94 per year for 3 m × 3 m corridor area. The potential electricity savings align with Sustainable Development Goal-11 by promoting energy efficient building solution that contribute to the sustainability of urban space.

1. Introduction

Buildings currently contribute to approximately one-third of global energy consumption and nearly a quarter of CO_2 emissions [1], [2]. In Malaysia, artificial lighting is the second-largest contributor to building energy use after air conditioning, accounting for around 20% of total electricity consumption [3]. Although Malaysia benefits from abundant sunlight throughout the year, many buildings remain dependent on artificial lighting, especially during early mornings, late evenings, or cloudy weather.

Integrating natural daylight into buildings has emerged as a sustainable approach to reduce energy demand and enhance occupant well-being. Natural light not only reduces heat gain from artificial sources, particularly in tropical climates, but also positively influences biological and psychological functions [1], [4]. One of the technologies supporting this effort is the light pipe system, which channels daylight through reflective tubes into indoor spaces. However, these systems are typically effective for only five to six hours per day under optimal sunlight [3].

To address these limitations, this study focuses on developing a light pipe system integrated with photovoltaic (PV) solar panels and LED lighting. This system aims to provide continuous indoor lighting throughout the day by storing solar energy and activating LED lights when natural light is insufficient. A 1:10 scale windowless room model was constructed for this research, incorporating a reflective light pipe, PV panel, light sensor, and LED strip. The model was placed outdoors at UTHM Pagoh and tested under real conditions over three sunny days. Illuminance readings were collected hourly from 8:00 a.m. to 6:00 p.m. using a lux meter

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to assess system performance and compliance with Malaysian Standard MS 1525 on recommended indoor lighting levels.The expected outcome is a low-cost, energy-efficient lighting solution that can reduce artificial lighting use by up to 60%. This system supports Malaysia's goal of achieving net-zero carbon emissions while improving the quality and comfort of indoor environments.

1.1 Literature Review

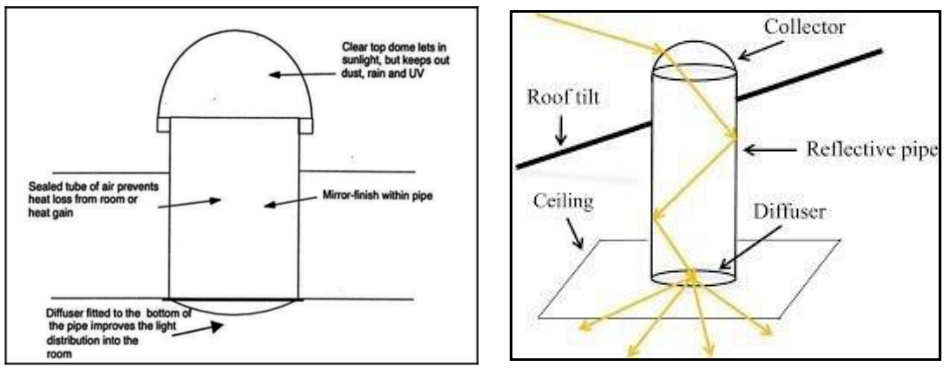
A passive architectural design that provides energy conservation, improved quality of indoor lighting, and well-being of occupants is called daylighting. [5] observed that sufficient daylight enhances visual comfort, mental health and productivity. As shown in Table 1, MS 1525:2019 in Malaysia provides recommended average illuminance values in different spaces which can be used as design targets of energy-efficient buildings. One popular system is the light pipe, also known as Tubular Daylighting Device (TDD), that collects sunlight in a dome, then directs it through a reflective pipe and spreads it inside with a diffuser [6].

Design factors influence the performance of light pipes and include pipe diameter, length, aspect ratio, internal reflectivity, orientation, and diffuser type. These characteristics are depicted in Fig. 1. In Fig. 1(a), the schematic shows a typical light pipe where a clear top dome allows sunlight to enter while preventing dust, rain, and UV rays. The sealed tube prevents heat loss or gain, and the mirror-finish inner surface ensures efficient light transmission. The diffuser at the end distributes light into the room. In Fig. 1(b), sunlight enters through a collector on the roof, travels down a reflective pipe, and is spread evenly by the diffuser at the ceiling level.

Advantages of light pipes are that they eliminate or reduce the need to use artificial lighting during the day, decrease the energy expenditure and also create a cooler interior environment which is beneficial to a deep-plan or a windowless room. They are, however, hampered by the availability of the sun and thus they perform optimally during the high-sun light hours (five to six hours a day). The performance is reduced in low-light periods. Light pipes may be combined with photovoltaic (PV) panels and LEDs, and light sensors to enhance reliability. PV panels collect solar energy and sensors turn on the LEDs when the daylight is below a determined threshold. Integration combines cost and complexity, but results in consistent lighting and contributes to energy objectives in Malaysia.

Table 1 *Recommended average illuminance level (MS 1525:2019)*

Task and Applications	Illuminance (Lux)
Corridor, passageways, stair	100
Entrance and exit	150
Toilet	100
Hotel bedroom	100
Lift interior	100
Bathroom	100



(a) **(b)**

Fig. 1 *Design (a) Schematic of typical light pipe; (b) sunlight passing through a light pipe*

1.2 Objective and Scope

The aims of this study is to explore a light pipe system integrated solar panel with LED in illuminating indoor area.There are three general objectives that would help in making buildings energy efficient by use of natural day lighting. First, it aims at developing a prototype of a light pipe system with solar panels which can play the

role of daylighting as well as energy production. Second, the experiment will involve measuring the indoor illuminance levels when using the combined system in order to determine the system ability to generate adequate natural lighting. Third, is determining the energy-saving potentiality of this incorporated light pipe system through performing comparisons between its work and traditional lighting systems. The study scope is centered in testing this system with a 1:10 scaled model of a windowless room, which will be tested in the real outdoor conditions at UTHM Pagoh campus. The data is collected after measuring during three sunny days to provide credible results. The outcome should be able to shed some light on the applicability of the system on the tropical climate such as Malaysia wherein optimization of natural sunlight can save a substantial amount of electricity.

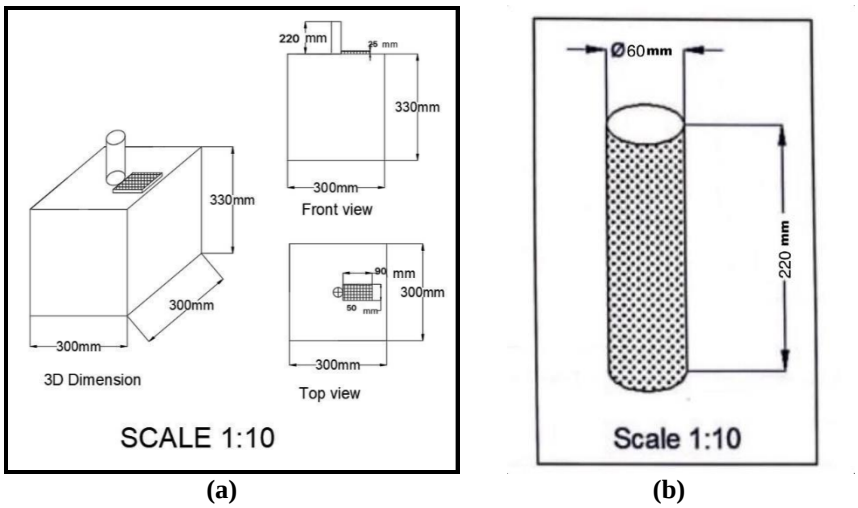
2. Methodology

Light pipe system is an approach used to improve daylight penetration as to reduce the dependency on artificial lighting during daytime. It is the easiest way of improving energy efficiency and attaining energy saving. In order to assess the performance of a novel light pipe system integrated with solar panels, this study used an experimental method by building a 1:10 scale model. The process was divided into three stages: prototype design and fabrication, field measurements, and energy savings to estimate indoor illuminance in real life situations. The main purpose of this study was to determine the performance of the light pipe system in distributing daylight efficiently and sustaining appropriate lighting levels for indoor environments.

2.1 Design of Light Pipe System with Integrated Solar Panels

The prototype was constructed as a windowless room model with dimensions of 300 mm × 300 mm × 330 mm, designed to simulate an enclosed interior space with no access to natural lighting (Fig. 2 (a)). A vertical cylindrical light pipe with a diameter of 60 mm and height of 220 mm had been fitted at the top of the model (Fig. 2(b)). The light pipe is the primary element for transmitting natural daylight from the exterior to the interior of the model. Additionally, advanced reflective materials and optical designs, as highlighted by [7], enhance daylight distribution by directing sunlight deeper into buildings, ensuring uniform illumination and reducing energy consumption. Inside, the inner surface is lined with highly reflective aluminum sheeting or reflective fabric capable of reflecting 95-98% of incoming sunlight internally, thus cutting down on loss while the light is in transit.

A light sensor (OPT3001) was placed inside the model to record actual internal illuminance levels and collect credible light intensity data throughout the day. In addition, a mini camera was placed inside the structure to take visual recordings of the impact of lighting and performance at different times and angles. This design allowed to observe the distribution patterns of natural light in the space and assess how effective the light pipe system is under real sunlight, especially with varying daylight conditions.



(a) **(b)**

Fig. 2 *Dimension (a) windowless room model scale 1:10; (b) light pipe tube*

2.2 Field Measurement

Field measurements were carried out over five consecutive days at an open area behind the residential college at UTHM Pagoh Campus. The location was chosen because it gets plenty of natural light, so it's suitable to test

the light pipe system under the optimum daylight conditions. The main objective of this phase was to evaluate the level of indoor illuminance achieved through the light pipe system under various weather conditions.

The room model was set up outdoors on a table at UTHM Pagoh Campus to ensure full exposure to natural sunlight. A lux meter was used to measure both external and internal light levels. The sensor was placed on top of the model to record outdoor illuminance and at the center of the model floor to measure indoor lighting levels. Data were recorded every hour from 8:00 a.m. to 6:00 p.m. using a lux meter (model LX1010BS). Outdoor readings were recorded by placing the sensor on top of the model, while indoor readings were taken at the center of the model floor to represent actual light levels inside the room (Fig. 3) . The weather conditions like sunny, cloudy, or rainy were also noted every hour to enable appropriate analysis. The collected data helped evaluate the effectiveness of the light pipe system in maintaining adequate indoor illuminance levels throughout the day, in line with building lighting standards such as MS 1525:2019.

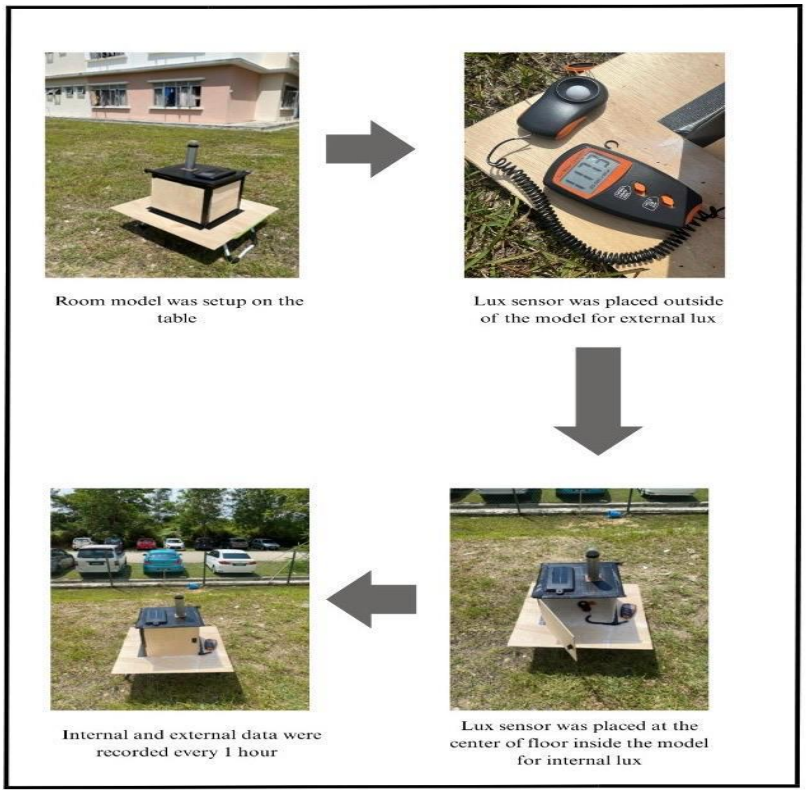


Fig. 3 *Method of collecting data*

2.3 Energy Saving Using Fluorescent Tube

The fluorescent tube is a commonly used electrical appliance in Malaysian buildings, especially offices and residences [8]. Therefore, for the purpose of calculating energy savings, the use of an electrical fitting 2 × 18-Watt ceiling recessed was considered. This type of lighting fixture is frequently used in office settings due to its practicality and efficiency. By selecting this common configuration, the study aims to provide realistic estimates of potential energy savings that can be achieved through lighting retrofits or the incorporation of daylighting systems in similar environments.

Natural daylight is an important resource for reducing energy use in buildings. Its application in building design is gaining attention because it helps save energy. Several studies have shown that effective daylighting strategies can lower a building's energy demand and improve energy efficiency, while also reducing environmental pollution [9], [10, [11]. Studies also found that the impact of daylight is not continuous due to the existing daylight system in buildings, and it does not cause pollution.

The total daily energy consumption (EC) is determined by multiplying the total number of lamps (N), the wattage of each lamp (W), and the total hours of operation (OH). The formula is expressed in equation (1):

$$EC = \frac{(N \times W \times OH)}{1000} \quad (1)$$

The total energy saving (ES) in equation (2) can be calculated as the difference between the energy consumption of the current lighting system ($EC_{Current}$) and that of the retrofitted system ($EC_{Retrofitting}$).

$$ES = EC_{Current} - EC_{Retrofitting} \quad (2)$$

3. Results and Discussion

This section presents the performance assessment of a novel light pipe system integrated with solar panels. The system was evaluated at the UTHM Pagoh campus using a 1:10 scale windowless room model. Data was recorded hourly from 8:00 a.m. to 6:00 p.m. over five days of field measurements.Two scenarios were studied: lighting performance using the light pipe system alone, and lighting performance using the light pipe system integrated with solar panels and LED support. Three parameters were measured during the study outdoor illumination, indoor illumination using only the light pipe system, and indoor illumination when the LED lighting was activated in conjunction with the integrated system. The analysis emphasizes maintaining lighting levels in accordance with MS 1525:2019, the Malaysian standard for energy efficiency in buildings. This part also addresses the third objective of the study, which is to assess the potential of the integrated light pipe system to reduce reliance on conventional artificial lighting, thereby contributing to energy savings.

3.1 LPS distribution

Based on Fig. 4, Day 1 demonstrated strong outdoor illuminance, peaking at 131,800 lux around noon. Indoor lighting using only the light pipe system (LPS) reached a high of 1,188 lux at 1:00 p.m., well exceeding the MS 1525:2019 minimum requirement. However, from 4:00 p.m. onwards, natural lighting fell below 100 lux, prompting LED assistance. This successfully boosted lighting back above the threshold, demonstrating the effectiveness of the integrated system. On Day 2, similar patterns were observed. Outdoor illuminance remained high during midday, while indoor illuminance peaked just under 900 lux. LED support was again crucial in the late afternoon to maintain acceptable lighting levels. On Day 3, despite variable weather, indoor lighting peaked at 870 lux by noon. Still, multiple hours particularly before 10:00 a.m. and after 3:00 p.m. showed indoor levels dipping below 100 lux. LED activation in these periods ensured compliance with MS 1525:2019 standards.

On Day 4 and Day 5, outdoor illuminance followed a similar bell-curve pattern. Peak readings ranged between 120,000 to 140,000 lux, which enabled the LPS to provide adequate indoor lighting during midday which is reaching over 600 lux. Yet, during early and late hours, natural lighting alone fell below the 100 lux mark. Based on Fig. 4, LED support was triggered during these low-light periods, consistently lifting illuminance levels back above the MS 1525:2019 minimum. These results affirm that while the light pipe system alone performs effectively under strong sunlight, the integration of LED assistance ensures reliable and compliant indoor lighting throughout the full day. This hybrid setup not only maintains user comfort but also reduces overall dependency on artificial lighting, contributing to energy savings in line with the study's final objective.

This observation is in line with the shortcoming of passive daylighting systems in situations with low solar angle, usually leading to an inadequate interior lighting in the early morning and late afternoon hours of the day [12], [13]. In this regard, it has been generally advised that hybrid daylighting approaches which incorporates daylight transport technologies like light pipes with energy-efficient LEDs should be adopted to provide a uniform observance of interior lighting requirements [14]. In general, the findings prove that the light pipe system, in isolation, is capable of sustaining sufficient levels of illuminance during about 70% of the daylight hours. Nevertheless, during the rest of the time (30% usually early in the morning and in the late afternoon), hybrid mode with LED add-on is still required.

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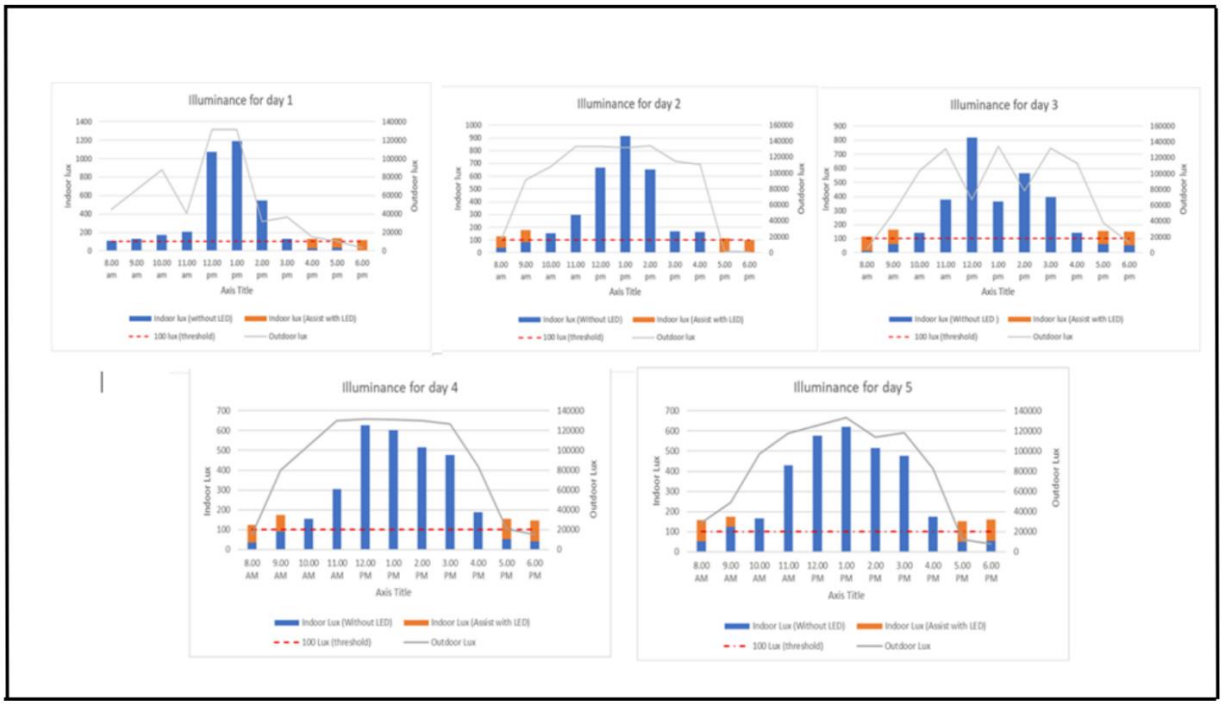

Fig. 4 *Illuminance for each day*

The average illuminance pattern over five days is shown in Fig. 5, which indicates that the MS 1525:2019-recommended minimum illuminance level of 100 lux is regularly reached between 10:00 a.m. and 4:00 p.m. Without the assistance of solar-powered LED illumination, this performance is entirely attributable to the Light Pipe System (LPS). According to MS 1525:2019, the system can meet the minimum daylighting standards for a variety of interior places within this time range, including hotel bedrooms, hallways, and restrooms.

However, when using LPS alone, illuminance measurements at 8:00 a.m., 9:00 a.m., 5:00 p.m., and 6:00 p.m. show a notable decrease below the necessary 100 lux threshold. Additional LED lighting is needed during these hours to achieve the illuminance levels needed for safety and visual comfort. The low solar height and reduced daylight availability in the early morning and late evening, which are regular constraints in passive daylighting systems, could be the cause of this deficiency. [12] made a similar discovery, pointing out that because of variations in solar position and sky conditions, daylight-linked lighting systems frequently need artificial lighting support during times of low ambient light.

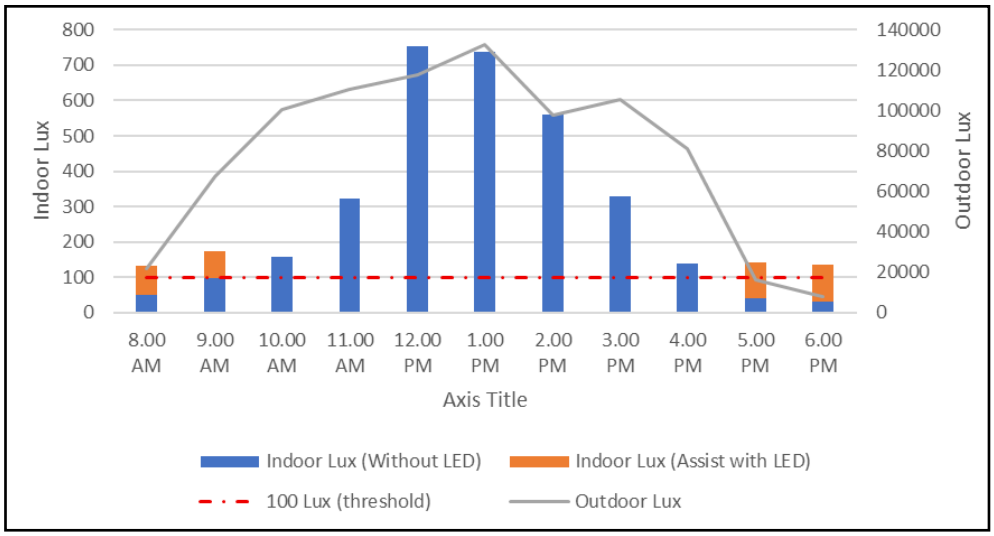

Fig. 5 *Average illuminance over 5 days*

3.2 Energy saving

Artificial lighting remains an essential component in nearly all types of buildings, even when daylighting strategies are effectively applied. This is particularly relevant for areas used at night, spaces with limited access to natural light, or situations where daylight alone does not meet the required illumination levels. However, in environments primarily occupied during the day such as office spaces the reliance on artificial lighting can be significantly reduced. For instance, a 3-meter by 3-meter room equipped with a 2 × 18 Watt recessed ceiling luminaire typically consumes approximately 0.36 kWh of electricity per day, a value that can be calculated using equation (1). Through field testing of the Light Pipe System (LPS) integrated with Light Emitting Diodes (LEDs), it was found that up to 10 hours of natural daylight could effectively offset or eliminate the need for artificial lighting in such spaces.

$$EC = \frac{2 \times 18 \times 10}{1000} = 0.36 \text{ kWh} \quad (3)$$

With the current electricity rate in Malaysia set at RM 0.4562 per kWh, this translates to an estimated daily cost of RM 0.164. By replacing artificial lighting with a Light Pipe System (LPS) combined with LEDs for the same duration, the daily energy savings (ES) is 0.36 kWh, which can be determined using equation (2). As shown in the detailed calculations in Table 2, this results in potential cost savings of RM 0.16 per day, RM 1.15 per week, RM 4.93 per month, and approximately RM 59.94 per year.

Table 2 *Overall energy consumption in the test room*

	Without LPS (ES)	With LPS+LED (EC)	Cost Save (ES - EC)
Daily	0.36 kWh × RM 0.4562 = RM 0.16	-	RM 0.16 - RM 0 = RM 0.16
Weekly	2.52 kWh × RM 0.4562 = RM 1.15	-	RM 1.15 - RM 0 = RM 1.15
Monthly	10.8 kWh x RM 0.4562=RM 4.93	-	RM 4.93- RM 0= RM 4.93
Yearly	131.4 kWh × RM 0.4562 = RM 59.94	-	RM 59.94 - RM 0 = RM 59.94

4. Conclusion

In this study, the development, production, and testing of a hybrid lighting system with a combination of light pipe, solar panels, and automatic LED backup were explored. A 1:10 scale model was tested for five days with illuminance and energy performance measured to evaluate its use in windowless spaces. The tests revealed that the light pipe was capable of delivering sufficient natural light, especially in the hours between 11:00 a.m. and 2:00 p.m., often more than 700 lux without added artificial lighting. During low-sun periods like early morning, evening, or during cloud cover, the solar-powered LED system, controlled by a light sensor, provided comfort indoors by turning on automatically offering normal lighting throughout the day without the intervention of humans.

Energy-wise, the system reduced LED runtime to just three to four hours per day, realizing over 60% savings in lighting energy. Since the LEDs were being powered by solar energy only, the system was made operationally off-grid during the test, according to targets of zero-energy buildings. In summary, the light pipe system integrated with solar panel is a cost-effective and environmentally friendly indoor lighting system. It maximally combines natural and renewable energy in minimizing electricity usage, enhancing indoor comfort, and addressing the green building and sustainable cause of Malaysia. Potential future studies could explore its large-scale applications, creative light pipe designs, and smart automation features. This aligns directly with Sustainable Development Goal (SDG) 11 which is sustainable cities and communities, which promotes inclusive, safe, resilient, and sustainable urban environments.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirms their contribution to the paper as follows: ***study conception and design****: Muhammad Naufal Hakimi Hamdan, Ahmad Zaim Zharfan Mohd Azizul Fahmi, Muhammad Harith Abd Rahman;* ***data collection:*** *Muhammad Naufal Hakimi Hamdan, Ahmad Zaim Zharfan Mohd Azizul Fahmi, Muhammad Harith Abd Rahman;* ***analysis and interpretation of results:*** *Muhammad Naufal Hakimi Hamdan, Ahmad Zaim Zharfan Mohd Azizul Fahmi, Muhammad Harith Abd Rahman;* ***draft manuscript preparation:*** *Muhammad Naufal Hakimi Hamdan, Ahmad Zaim Zharfan Mohd Azizul Fahmi, Muhammad Harith Abd Rahman, Aslila Abd Kadir. All authors reviewed the results and approved the final version of the manuscript.*

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