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Study of LED Retrofit Lamps in HSPV Luminaires Based on Photometric Method for Road Lighting

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ABSTRACT

Energy reduction is a great challenge in road lighting applications. Replacing high-pressure sodium vapor (HPSV) with light-emitting diodes (LED) is a viable approach to reducing energy consumption. However, a total replacement can incur a significant capital cost. This study aims to investigate the effects on light distribution by replacing HPSV lamps with LED lamps in HPSV luminaires using Light Intensity Distribution (LID) curve measurement and Backlight, Uplight and Glare (BUG) rating evaluation to reduce the adoption costs. While LED lamps have high illumination rates, the structural differences from HPSV lamps can affect the LID curve and original lighting design. Therefore, it is crucial to study photometric dispersion after retrofitting light sources. Both lamps were installed into similar HPSV luminaires to assess photometric performance using goniophotometer measurements. The HPSV lamp outperforms the LED lamp in terms of luminous flux (11.13%) and light intensity (7.69%), whereas the LED lamp outperforms the HPSV lamp in terms of efficacy rating (68.67%) and wattage used (47.61%). The findings indicate that retrofit LED luminaires have an LOR of 46.77% lower than the HPSV luminaires. The light distribution pattern is maintained but reduced to 40 to 50% for the main usable light angles. The reduced performance is caused by the lamp structure, which occupies a large area inside the luminaire housing, obstructing proper light distribution. Although overall energy consumption is reduced, similar illumination

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levels cannot be maintained. These outcomes can assist authorities and manufacturers with alternative methods of reducing costs while maintaining lighting levels.

Keywords: High-pressure sodium vapor, light emitting diode, light intensity distribution curve, light output ratio

INTRODUCTION

Choosing a light source that defines the cost, visual performance, and energy consumption is one of the main components of the lighting system (Rofaie et al., 2022). High-pressure sodium vapor (HPSV) lamp is currently used for road lighting in Malaysia due to its lower price. However, the current trend is moving towards energy-efficient lighting, such as light-emitting diodes (LEDs) and plasma induction (Grau et al., 2021). In 2018, Tenaga Nasional Berhad (TNB), one of the main electrical energy providers in Peninsular Malaysia, replaced over 212 639 units of 150W HSPV luminaire with LED luminaire, which has contributed to 30 to 40 % energy reduction (BERNAMA, 2023). The Public Works Department of Malaysia (PWD) also released a guideline in 2013, revised in 2018, on using energy-efficient light sources such as LED, induction lighting and eco-sodium light lamps (Jabatan Kerja Raya, 2018). In 2015, the EU decided to phase out light sources with hazardous material from 2021 to 2027 (https://eur-lex.europa.eu/eli/dir_del/2022/275/oj). By the year 2027, current HPSV lamps will be phased out and replaced by more energy-efficient light sources. The current method of using LED light source is a comprehensive conversion, which involves replacing the entire HPSV luminaire with a new complete LED luminaire, which comes at a high upfront expense (Bamisile et al., 2016; Kovačević et al., 2022). Even though this is a promising factor, the total replacement of HPSV luminaires with LED luminaires for each road requires a large capital cost.

Another approach lighting manufacturers introduced is replacing the HPSV lamps with LED replacement lamps while maintaining the original HPSV luminaire housing (Philips, 2023). Lamp conversion is common for indoor installations but rarely carried out in road lighting installations (Braga et al., 2014). Even though there are many types of LED retrofit lamps, research on the light distribution impact for road lighting applications is limited compared to indoor applications due to many safety requirements involving road lighting applications (Gordic et al., 2021; Rofaie et al., 2022). Thus, photometric parameters that describe the light performance of luminaire, such as the light intensity distribution, light intensity at angle, light output ratio and total luminous flux, are important to design the required illumination level for a given space, whether for indoor or outdoor lighting designs (Abdullah et al., 2021). For road lighting or public lighting, sufficient illumination is required to reduce traffic accidents (Li et al., 2023; Setyaningsih & Candra, 2023). Two roadway photometric criteria (horizontal illuminance and lighting uniformity) were investigated, and the matched case-control method was applied to decouple the illuminance average and standard deviation (Li et al., 2023). DIAlux software simulation was used to find the most optimum photometric illuminance in road lighting freeways in Indonesia to comply with the standard SNI 7391:2008 and eventually reduce accidents at night (Setyaningsih & Candra, 2023). Compliance with safety requirements is an important factor and should not be neglected. DIAlux software has also been used to analyze the changes in road lighting in terms of luminaire and pole spacing (Zima & Ciepłucha, 2023). Besides general properties of luminaires such as total luminous flux, wattage, and power factor, the luminous intensity distribution (LID) curve, which describes the output of luminaires at various angles, is one of the main pieces of information for calculating or simulating lighting designs (Bergen, 2012). LEDs are also superior to HPSV lamps in terms of visual acuity due to the higher color rendering index (CRI) and visual capabilities. Studies have shown that a lower lumen output of LED lamps is sufficient to match higher lumen values from HPSV lamps (Brons et al., 2021). Modeling techniques on comparison of HPSV and LED luminaires concluded that LEDs are marginally higher in average luminance per watt increment of luminaire power than HPSV luminaires (Bhattacharya et al., 2023). Studies on the photometric impact of replacing the original light source are limited (Abdullah et al., 2021). Recent studies regarding LED measurement have shown that LED has different characteristics than conventional luminaires and may require different measurement approaches for correct evaluation (Czyżewski, 2023).

HPSV is the current lamp utilized nationwide but is shifting towards energy-efficient light, such as LED lamps (BERNAMA, 2023). Fully LED road lighting requires a high investment cost for full implementation, including the lamp, luminaire and circuit (Rofaie et al., 2022). Back in 2012, when Malaysia started implementing LED lighting on roads, The Electrical and Electronics Association of Malaysia (TEAAM) did not recommend the usage of LEDs due to factors such as energy savings, cost savings, safety and security and environmental impact (TEEAM, 2012). However, advancements in lighting technology and updated standards in ensuring the safety of road LED light sources have become one of the main options for replacing HPSV lighting to reduce energy usage. In order to ensure the safety of road users, the laminated road has to meet the requirements of MS 825:2007; Code of Practice for The Design of Road Lighting-Part 1: Lighting of Roads and Public Amenity Area and BS EN 13201-2:2015 Road lighting Part 2: Performance requirements, in terms of performance parameters such as luminance value, overall uniformity, longitudinal uniformity, glare rating and glare index class. In contrast to the HPSV lighting system, LEDs are point light sources that are prone to cause glare toward road users if designed incorrectly (Ying & Lim, 2022).

This research aims to study the performance of LED and HSPV lamps based on photometric methods to look at the suitability of the LED lamp in HSPV luminaire. Replacing the HSPV lamp with an LED lamp in the HSPV luminaire housing can reduce cost compared to replacing the whole unit, but the lighting needs to be sufficient to ensure the safety of road users. Thus, a photometric analysis of LED and HPSV was implemented to observe both lamps' light distribution properties and performance. Light Intensity Distribution Curve (LIDC) changes were observed for both lamps based on photometric measurement. This study focuses on efficacy rating, wattage, luminous flux and light output ratio of the luminaire using the goniophotometric method and comparative analysis.

METHODS

Figure 1 shows the flow chart of the experimental method. The measurement process consists of equipment calibration and setting of equipment, measurement of bare lamps, and measurement of lamps inside light fittings. The comparison focuses mainly on the LID curve and Backlight, Up-light and Glare (BUG) rating. The test samples consist of an HPSV lamp (150W) and an LED Lamp (68W), as in Figure 2 (a and b), where the 150 W HPSV lamp was used as the basis for analysis of the 68 W LED lamp. The 68 W LED lamp is a surface-mounted device (SMD) type LED chip mounted on a circuit board with a heat sink (Philips, 2023). The light fixtures of both lamps are similar, as shown in Figure 2(c). Specification of the test sample is shown in Table 1.

This study was conducted in a laboratory environment at an ambient temperature of 25 ± 2°C and relative air humidity of <50% with reference to standards CIE 121:1996 (International Commission on Illumination, 1996) and CIE DIS S025:2015 (Bredemeier, 2017) to ensure stability and reliability of the measurement. Figure 3 (a and b) show the photometer sensor and light baffles used in the experiment. The test sample was mounted and measured on the Rotating Luminaire Goniophotometer (Figure 3c) and tested based on C-γ coordinate system measurement. Measurement was repeated 10 times with a standard error of 0.01 to look at any reading discrepancies and to ensure the reliability of the experiment.

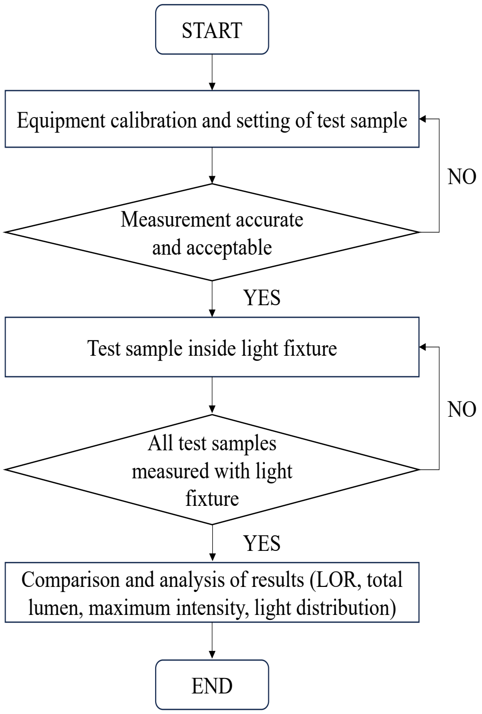


Figure 1. Flow chart of experimental measurement


(a) (b) (c)

Figure 2. Test sample used in the study: (a) HPSV lamp, (b) LED retrofit lamp, (c) 150 W HPSV light fixture

Table 1
Specification of the light sources

PARAMETER	HPSV LAMP	LED LAMP
Wattage	150 W@240 V	68 W@ 240 V
Rated Luminous Flux	13,500 lm	12,000 lm
Correlated Color Temperature (CCT)	2000K	4000K
Burning Orientation	Any	N/A
Screw Head Type	E40	E40


(a) (b) (c)

Figure 3. The main components of a goniophotometer: (a) a Photometer sensor, (b) light baffles, (c) a Goniometer sample mounting stage and test sample

The LED replacement lamp utilizes the same lamp base as the original HPSV lamp, allowing easy installation without any modifications to the existing luminaire. The test sample installed in the HPSV road light fitting is shown in Figures 4 and 5. The test was conducted by initially measuring the LID curve of each lamp before installing it into the sample road light fittings to compare both light distribution characteristics prior to installation into the luminaires. The luminaires were mounted vertically on a Rotating Luminaire Goniophotometer to the C-axis as in Figure 3(a), with starting coordinates based on the measurement of the C- γ coordinate system. Scan intervals were set at 15° for the C angle and 1° for γ angle.

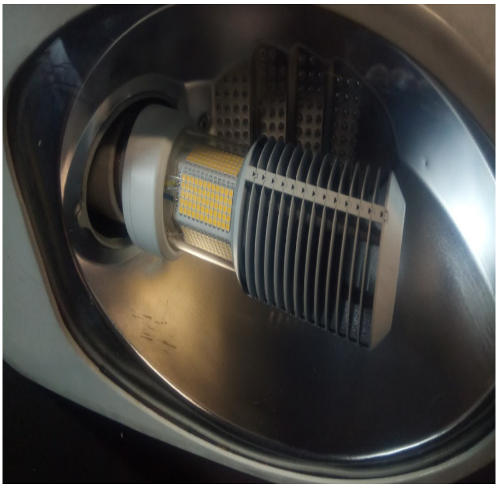


Figure 4. LED lamp in 150W HPSV light fixture

Figure 5. 150W HPSV lamp inside 150W HPSV light fixture

Analysis Methods

Results were analyzed based on a comparison of the original HPSV lamp and LED retrofit lamp in terms of the light output ratio (LOR) (International Commission on Illumination, 1996) and light output distribution angle percentage value based on the backlight- uplight-glare rating value (Chinnis et al., 2011).

Calculation of LOR is done based on Equation 1.

$$\text{LOR}=\frac{Luminaire\ Total\ Luminous\ Flux}{Bare\ Lamp\ Total\ Luminous\ Flux}. \qquad [1]$$

Zoning classification regarding the light output region was based on the luminaire classification system zoning, also known as Backlight-Uplight-Glare (BUG) classification (LCS). The BUG system provides a numerical rating of luminaire based on the photometric distribution tested by the manufacturer. The BUG rating system was proposed due to its ability to evaluate luminaire distributions in the context of the impact of light emitted in the various solid angles of the LCS as they apply to light trespass, sky-glow, and glare. The zones are divided into three major zones, shown by the alphabet U, which applies to sky glow, G to glare and B to backlight or light trespass Figure 6.

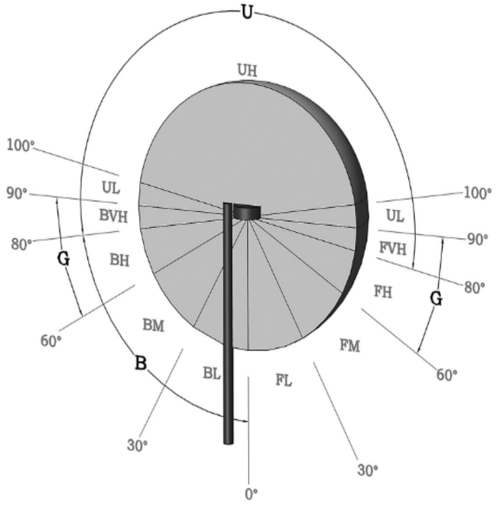


Figure 6. Zones for luminaires classification: UL (Up Light), FVH (Front Very High), FH (Front High), FM (Front Mid), FL (Front Low), BVH (Back Very High), BH (Back High), BM (Back Mid), and BL (Back Low) (IES TM-15:2007)

RESULTS

Light Output of Light Source

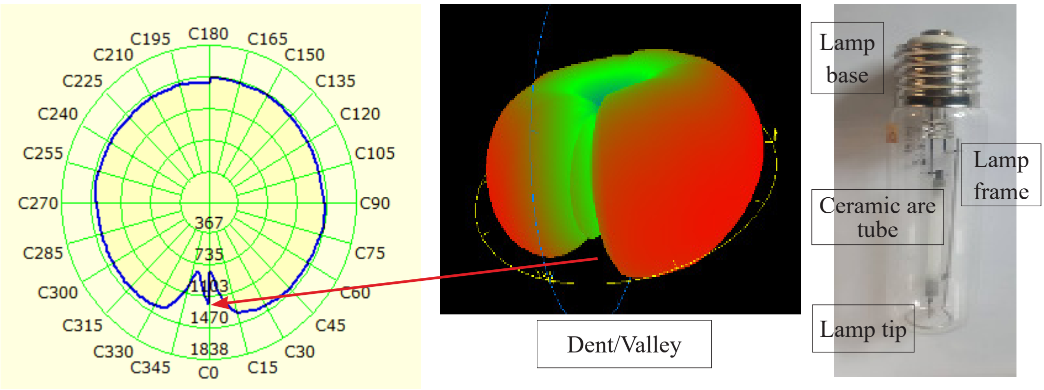
Table 2 shows the measured photometric properties of the HSPV lamp and LED lamp. The difference between the measured and manufacturer’s values is attributed to the different measurement methods where the measured values are from goniophotometric measurements. The integrating sphere method is normally used to measure the total luminous flux. Goniophotometric measurement is chosen here to monitor and analyze the light distribution pattern.

Figure 7 shows the 3-dimensional (3D) rendering of the Light Intensity Distribution (LID) Curve of a bare HPSV lamp. The light distribution is a doughnut shape with no light from the base and tip of the lamp. The light distribution has a slight dent or valley due to the frame structure blocking the light output, which can be seen in the 2-dimensional polar plot diagram at 90° vertical axis.

Figure 8 shows the 3-dimensional rendering of the LED retrofit lamp's Light Intensity Distribution (LID) Curve. The light distribution is a form of hexagonal shape with a similar resemblance to the HPSV bare lamp distribution results. The hexagonal shape shown in Figure 8(a) is due to the construction of the LED retrofit lamp comprising 6 faces of LEDs.

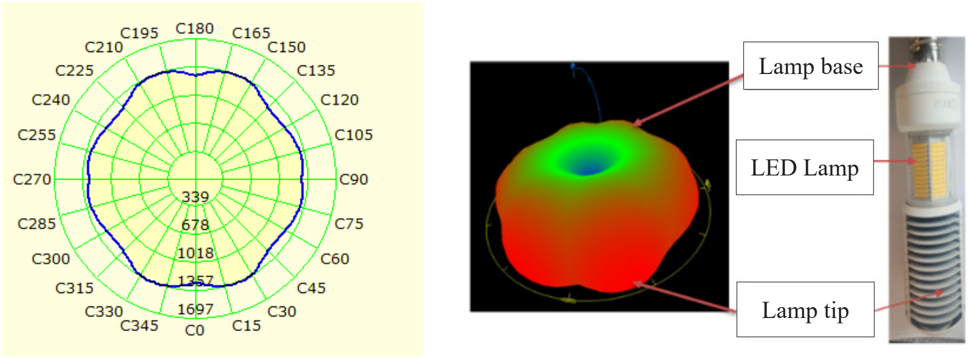
Table 2
Luminous flux output of HPSV lamp and LED lamp

Parameters	HPSV Lamp		LED Lamp	
	Measured Value	Manufacturer’s Value	Measured Value	Manufacturer’s Value
Luminous Flux	13,350 lm	13,500 lm	11,864 lm	11,200 lm
Efficacy Rating	83 lm/w	98 lm/w	140 lm/w	164 lm/w
Wattage	160.8 W	147.0 W	84.7 W	68.0 W



(a) 2D polar diagram (b) 3D polar diagram (c) HPSV light source

Figure 7. Polar diagram of HPSV lamp light at 90 vertical axis output and equivalent 3D rendering

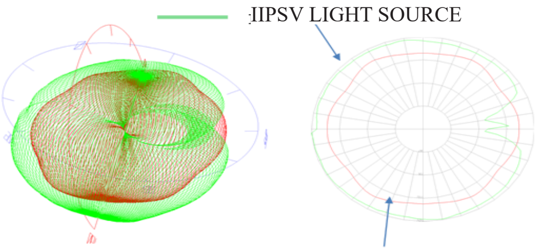


(a) 2D polar diagram (b) 3D polar diagram (c) LED light source

Figure 8. Polar diagram of LED lamp at 90 vertical axis output and equivalent 3D rendering

Comparison of HPSV and LED Retrofit Lamp

Figure 9 shows the 3D line rendering and 2D polar plot comparison of both HPSV and LED lamps. The green rendered line is for the HPSV lamp, while the red is for the LED retrofit lamp. The LED retrofit lamp has a similar doughnut-shaped output to the HPSV lamp. It shows the compatibility of replacing the LED retrofit lamp with the HPSV fitting due to similar luminous flux. The characteristics of luminous output value are shown in Table 3.



(a) 3-D Line rendering comparison (b) 2D polar plot comparison

Figure 9. Polar diagram of LED lamp at 90 vertical axis output and equivalent 3D rendering

Table 3
Luminous output comparison of HPSV and LED retrofit lamp

	HPSV Lamp	LED Retrofit Lamp	% Difference
Luminous Flux	13,350 lm	11,864 lm	- 11.13%
Efficacy Rating	83 lm/w	140 lm/w	+ 68.67%
Wattage	161.78 W	84.75 W	- 47.61%
Maximum Intensity	1470.93 cd	1357.72 cd	- 7.69%

LIDC Comparison of HPSV And LED Retrofit HPSV Luminaires (150 W)

The LID curve of the LED retrofit lamp and the original LID curve of the HPSV lamp are compared in Figure 10. The original LID curve of the HPSV luminaire is represented by the red shade of the LID curve, while the green shade of the LID curve represents the LED lamp retrofitted HPSV luminaire. A significant drop in the luminaire's light distribution can be observed from almost all angles. The decline is visible in the 0%–180^o and 90–270^o regions. Table 4 compares the HPSV and LED retrofit lamps used in 150W HPSV fitting. From the results, a reduction of total lumen output from 11,146 lm to 5,807 lm can be seen clearly. There is an insignificant change in the efficacy rating of 67 lm/w for HPSV lamps compared to 69 lm/w for LED retrofit lamps, possibly due to the higher wattage of the HPSV lamp. The efficiency of the fitting has also reduced to 49% from an initial efficiency of 83% by using the LED retrofit lamp. Then, Figure 11 shows the lumen pie chart for (a) HPSV lamp and (b) LED retrofit lamp luminaire.

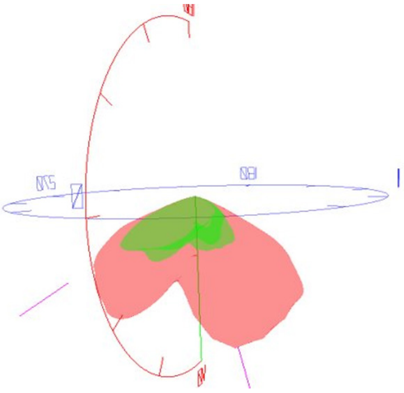
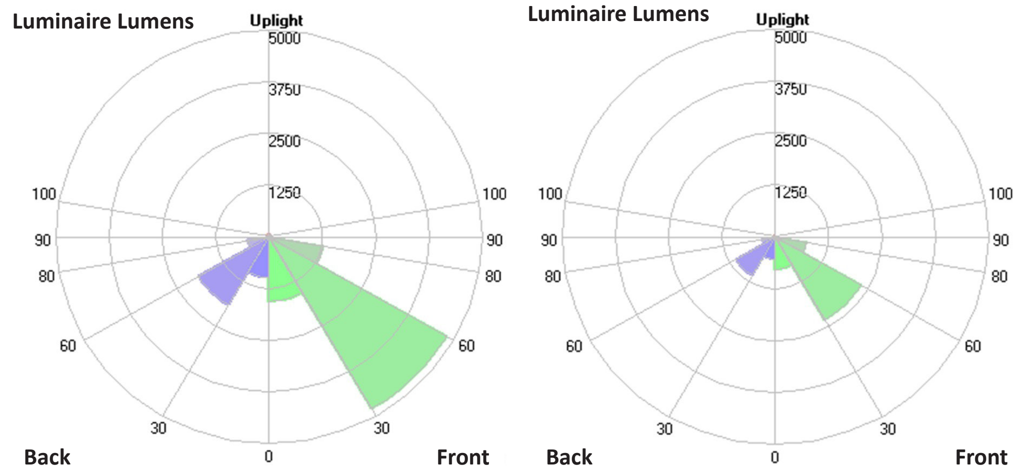


Figure 10. Comparison of HPSV lamp and LED lamp polar diagram with each lamp is placed inside 150 W HPSV light fitting using goniophotometric measurement

Table 4
Comparison of lumen output for HPSV lamp and LED retrofit lamp in 150W HPSV fitting

Description	150W HPSV LAMP	LED Lamp (Philips Trueforce LED Lamp 68 W)
Lumens Per Lamp	13,350 (1 lamp)	11,858 (1 lamp)
Total Lamp Lumens	13,350	11,858
Luminaire Lumens	11,146	5,807
Downward Total Efficiency	83%	49%
Total Luminaire Efficiency (LOR)	83%	49%
Luminaire Efficacy Rating (LER)	67	69
Total Luminaire Watts	166.72	84.18
LCS: Total Lumens	11,146	5,807



(a) HPSV lamp

Luminaire Lumens:
Front : Low = 1557.1, M = 4795.7, High = 1295.3, Very High = 27.2
Back : Low = 987.2, Medium = 1902.0, High = 504.9, Very High = 12.3
Uplight: Low = 7.1, High = 56.9

(b) LED retrofit lamp

Luminaire Lumens:
Front : Low = 783.4, M = 2311.6, High = 744.8, Very High = 24.3
Back : Low = 537.5, Medium = 1066.5, High = 597.1, Very High = 8.4
Uplight: Low = 4.3, High = 29.1

Figure 11. (a) HPSV lamp, (b) LED retrofit lamp luminaire lumen pie chart

Based on the two-lumen pie charts in Figure 11, it can clearly be seen that the proportion of lumen output per distribution angle is almost identical, with the luminaire maintaining its forward and backward light distribution. However, there is a reduction to about half of the original light distribution for the retrofit LED lamp. The front-mid angle has decreased from 4,795.7 lumens to 2,311.6 lumens, a 51% reduction in lumen output. The average drop of 40% is similar to other elevation angles. Table 5 compares the HSPV lamp and LED lamp based on elevation angle. There is no significant change in glare rating when the HPSV lamp is changed to an LED lamp except for reduced glare from G1 to G0 at "Back Very High Elevation." A lower glare rating indicates a lower level of glare.

Table 5
Light output comparison of HPSV and LED retrofit lamp per elevation angle

Elevation Angle	Hpsv Lamp (Lumen)	Lamp Glare Rating	Retrofit LED Lamp (Lumen)	LED Lamp Glare Rating	% Reduction
Front Low	1557.1	-	783.4	-	49.68
Front Medium	4795.7	-	2311.6	-	51.7
Front High	1295.3	G1	744.8	G1	42.4
Front Very High	27.2	G1	24.3	G1	11.02
Back Low	987.2	-	537.5	-	45.55
Back Medium	1902.0	-	1066.5	-	43.92

Table 5 *(Continue)*

Elevation Angle	Elevation Angle	Lamp Glare Rating	Retrofit LED Lamp (Lumen)	LED Lamp Glare Rating	% Reduction
Back High	504.9	G0	297.1	G0	41.11
Back Very High	12.3	G1	8.4	G0	31.70
LCS: Total Lumens	11,146	-	5,807	-	46.77

Due to the lamp structure, which occupies a large area inside the luminaire's housing, the output performance of the LED retrofit lamp is significantly reduced. Figures 3 and 4 show the retrofit LED and HPSV lamps inside the luminaire housing, respectively. Compared to the HPSV lamp, the LED retrofit lamp has taken up more than half of the space inside the HPSV luminaire, obstructing the LED lamp's light output.

DISCUSSION

In this research, a much cheaper method is utilized where the HPSV lamp is replaced with an LED lamp of similar luminous output to determine the suitability of using such a method. The different solutions can be utilized and give benefits in terms of better color rendering visibility at a cheaper cost. The lamp replacement may be an alternative method to total luminaire replacement by the local government. The study uses photometric measurement to analyze changes in light distribution, and analysis is also done based on Backlight-Uplight and Glare ratings.

From the results of the photometric measurement, it was found that installing the LED lamp inside the luminaire caused a reduction in the total light output ratio. The light distribution pattern was maintained but with a 40–50 % reduction at all backlight and front light angles. The glare was still controlled, whereas the rating was still maintained. It also resulted in an overall luminance value of 52% based on the lighting simulation.

The main focus of the study is to compare the light output ratio (LOR) using two types of lamps applied in Malaysia, HSPV and LED lamps. The LED lamp replaces the original HPSV lamp in the HSPV luminaire. The LOR value is chosen as an indicator of the ability of the road lighting fixture to produce output light from the installed lamp towards the illuminated area. In terms of construction, both lamps have different lamp structures where the LED lamp is larger compared to the HSPV. The LOR and backlight, uplight and glare (BUG) rating parameters can be applied as an initial stage to choose a suitable road lighting system without any energy waste. Other parameters such as average road luminance, brightness uniformity, longitudinal uniformity, glare, surround ratio (SR), color rendering index (CRI) and visual inducement are also important for road lighting. However, LOR and BUG rating parameters are much needed for the initial stage of lamp selection.

The LOR and BUG rating parameters differ from the street lighting design parameters, such as average luminance, uniformity and glare, where those parameters require a longer lighting simulation or measurement for the analysis.

The latest road lighting standard has implemented the scotopic /photopic ratio in evaluating road lighting measurement and design. This value will benefit light sources with a spectral distribution tilted towards the lower wavelength, such as LEDs. The mid-range mesopic visibility region for road lighting is evaluated at low luminance values. It enables designers to design a system with lower electrical consumption while maintaining the required lighting levels. The luminous intensity class and glare ratings requirements have also been included (British Standard, 2015).

In general, LED lighting is a solid-state device with no moving parts. Based on the manufacturer's data, the LED lamp has a lifetime capability of 50,000 hours, whereas the HPSV lamp has a lifetime capability of 25,000 (Philips, 2023). However, LEDs are prone to failure due to electrical control gear components, which will require thorough investigation (Lewotsky, 2011).

LED has a color rendering index (CRI) of above 70, while the HPSV lamp has a CRI of 35, much lower than that of LED (Philips, 2023). It shows that the LED has a better visual perception than the HPSV lamp, resulting in a lower luminance value requirement. Factors such as low luminance level illumination where the mesopic region is more sensitive to human sight will affect the visibility of road users. Further study on implementing mesopic evaluation for road lighting may increase the usability of LED lighting systems even at lower lighting levels. Then, the Light Intensity Distribution (LID) Curve of the light source describes the light propagation, which will directly impact the light falling on the road surface and direct surroundings. From the LIDC of the light source, important parameters such as total luminous flux of the light, luminaire efficacy (lm/w) and efficiency based on light output ratio (LOR) and Backlight-uplight dan Glare indicators can be identified and measured as well.

This research can assist the authorities in choosing whether to replace the whole HSPV luminaire with an LED luminaire or only the lamps. It is important to save installation costs while ensuring the required lighting level is sufficient. Previous studies indicated high capital cost in changing from HPSV to LED systems, and its feasibility depends on the energy conservation potential (Kovačević et al., 2022; Yousif et al., 2018). Due to limited resources, the study used HPSV luminaires with a "cobra head" design with only a single type of LED retrofit sample. Various types of luminaires, such as compound post-top luminaires and different LED retrofit lamp structures, may produce different outcomes.

CONCLUSION

In conclusion, the study shows the possibility of replacing HPSV lamps with LED retrofit lamps rather than replacing entire luminaires to save costs. Using more efficient lighting, such as LED, at a lower cost can be a promising solution. The photometric output of original HPSV lamps fitted streetlight and LED retrofit lamps are compared in this study.

According to the photometric results of the bare light sources, both have similar light output distribution, with most of the light coming from the sides of the lamps and almost no light from the tips. Thus, the retrofit method is a compatible replacement in terms of light distribution of the light source. The entire luminous flux of both lamps is similar, with a total lumen difference of 1492 lumens between the HPSV lamp and the LED retrofit lamp.

When the HPSV lamp fitting is retrofitted with the LED lamp source, the luminaire's performance is reduced to a 49% light output ratio (LOR) from an initial 83%. The proportion of lumen output per distribution angle is approximately identical for the luminaire's forward and backward light distribution. Compared to the HPSV lamp, which has a smaller structure, the LED retrofit lamp causes a considerable decrease in output performance since the lamp structure occupies a large area inside the luminaire housing, preventing the light output from the luminaire.

The findings can assist the government in looking at the advantages of LED over HSPV in upgrading road lighting that can finally benefit humans and the environment. Thus, local authorities and manufacturers can work together to study the best structure of luminaire housing. In the future, more LED samples will be tested to compare their performance based on photometric methods.

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