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Evaluation of a cost-effective photoelectric sensor for daylight harvesting in smart public lighting systems

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ABSTRACT

Global warming concerns, along with international agreements and regulations, reflect a broader effort to change the public's high energy demand in recent years. Smart public lighting systems are gaining popularity due to their energy-saving capabilities, reduction in carbon dioxide emissions, and improved public comfort. However, transitioning to smart public lighting requires careful planning and multiple stages. This is not only to accommodate public behavior, revise scenarios, and test citizen acceptance but also due to the necessary infrastructure investments. Smart public lighting incorporates new technologies, often with a breakeven point that takes several years to reach. To promote the widespread adoption of smart public lighting, it is essential to produce relatively expensive components in large quantities and explore cost-effective solutions. This research focuses on investigating a cost-effective photoelectric sensor for smart public purposes. The primary originality of this study lies in identifying a cost-effective photoelectric sensor that can replace technically equivalent but more expensive sensor solutions for indoor and outdoor lighting control purposes.

1. Introduction

Increasing awareness about the proper way to consume energy has heightened public expectations for reducing the energy consumption of common electrical loads. This shift involves upgrading luminaires to LEDs and integrating communication and control components into lighting systems for roads, streets, car parks, and other public areas, including indoor environments. Energy-efficient solutions for indoor public lighting are the focus of various studies. Gao et al. examined dynamic indoor lighting and the control of illuminance using LEDs [1]. Liu et al. explored energy savings through the use of a fuzzy controller for indoor lighting [2]. Moadab et al. compared conventional lighting with smart lighting in apartments [3]. Additionally, reducing fatal crashes and ensuring safety in public areas are other important research topics in smart public lighting [4,5].

Due to the implementation of new technologies in smart public lighting, it has been subject to regulations in recent years [6–8]. These regulations address aspects such as light quality, illumination levels for various locations, energy efficiency, efficacy, and dimming profiles. In the EU, illumination and uniformity standards vary depending on the specific subspace and its operations.

Public lighting is a significant subject of research due to its substantial share of energy consumption. Research focuses include control methods [2,9,10], installation costs, and the development of reliable and sustainable future concepts. Beccali et al. [11] and Logar et al. [12] investigated the use of daylight to save energy while maintaining acceptable indoor conditions. Sifakis et al. explored smart lighting in a harbor, presenting a new technique with three stages: reallocating and replacing obsolete luminaires, integrating daylight harvesting techniques, and implementing an occupation-based dimming strategy using actual data [13,14].

Photometric measurements alone are insufficient to capture how users perceive light, necessitating the development of additional tools. One such tool is the Perceived Outdoor Lighting Quality (POLQ) environmental assessment tool, as developed in Ref. [15]. Among various management strategies to reduce light pollution at night are options such as modifying the height of street lamps, adjusting lighting intensity, and altering spectral composition [16]. Lighting, both indoors and outdoors, is essential for daily life, with electric energy consumption in commercial buildings and households accounting for 20 %–40 % annually [17].

The transition from darkness to light varies throughout the year and occurs in phases around sunrise and sunset. Additionally, winter days and

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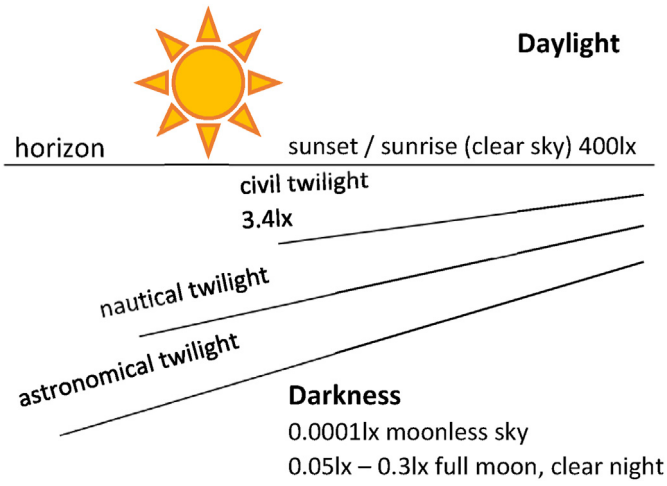


Fig. 1. Twilight phases.

certain weather conditions can have extended dark periods that require artificial illumination. The spectral composition of light also changes throughout the day [18]. Therefore, conventional public lighting systems that operate on a simple timer are often inefficient, as they may not provide adequate illumination at all times. Implementing a linear control system with light level sensor feedback can significantly reduce energy consumption and address the need for illumination during daytime hours.

Twilight is the period between daylight and darkness, occurring at both dusk and dawn when the sun is below the horizon but light still scatters through the atmosphere. Twilight is divided into three levels: civil, nautical, and astronomical. Civil twilight occurs when the sun is between 6° below the horizon and the horizon. Nautical twilight is when the sun is between 12° below the horizon and the horizon. Astronomical twilight is when the sun is between 18° below the horizon and the horizon [23].

For example, in Amiens, a city in Hauts-de-France, on October 14, 2021, the sun rises at 08:11 and sets at 19:01, providing 13 h and 10 min of daylight [24]. Civil twilight lasts 1 h and 5 min, nautical twilight lasts 1 h and 15 min, and astronomical twilight also lasts 1 h and 15 min, resulting in 9 h and 35 min of night. These twilight periods can be utilized for daylight harvesting based on the location's illumination requirements. Fig. 1 illustrates the stages of twilight.

Daylight harvesting, a method where some of the illuminance requirement is provided by natural daylight to reduce energy demand, is a prominent area of research in smart lighting [1,19,20]. This involves investigating effective daylight harvesting techniques and developing control methods to optimize its use.

In smart lighting systems, two types of sensors are commonly used.

1. Light level detection sensors to monitor illumination levels.
2. Presence sensors to detect the presence of a person or motion for safety and comfort.

A cost-effective light level sensor can be highly beneficial for implementing an illumination control system. This research explores the performance of such a sensor for smart lighting applications in both indoor and outdoor settings.

2. Methodology

Daylight harvesting involves utilizing ambient light to meet part of the lighting demand. The ambient light level is measured and subtracted from the required illumination, with the remaining need met by adjusting the dimming level. Fig. 2(a) and (b) illustrate outdoor and indoor daylight harvesting, respectively.

This research investigates the performance of a cost-effective phototransistor (PT) sensor for measuring light levels both indoors and outdoors. The selected PT sensor has a relative spectral sensitivity greater than 0.5 for wavelengths between 440 nm and 800 nm, with peak sensitivity at 570 nm. Its half-angle of sensitivity is ±60°, making it suitable for illumination sensing. It is mass-produced for digital devices, automotive applications, and dashboards, contributing to its cost-effectiveness. These low-cost photoelectric sensors can be highly effective for obtaining digital images and accurately estimating illumination [21,22]. The sensor's power dissipation is less than 100 mW.

However, the increase in the sensor's relative photocurrent with increased illuminance is not linear, and ambient temperature can also raise the relative photocurrent. Additionally, the varying spectral composition of light and outdoor solar illumination throughout the day can reduce the accuracy of the sensor's output for illumination feedback [18]. To address this, a matte plastic material, a semi-transparent sheet

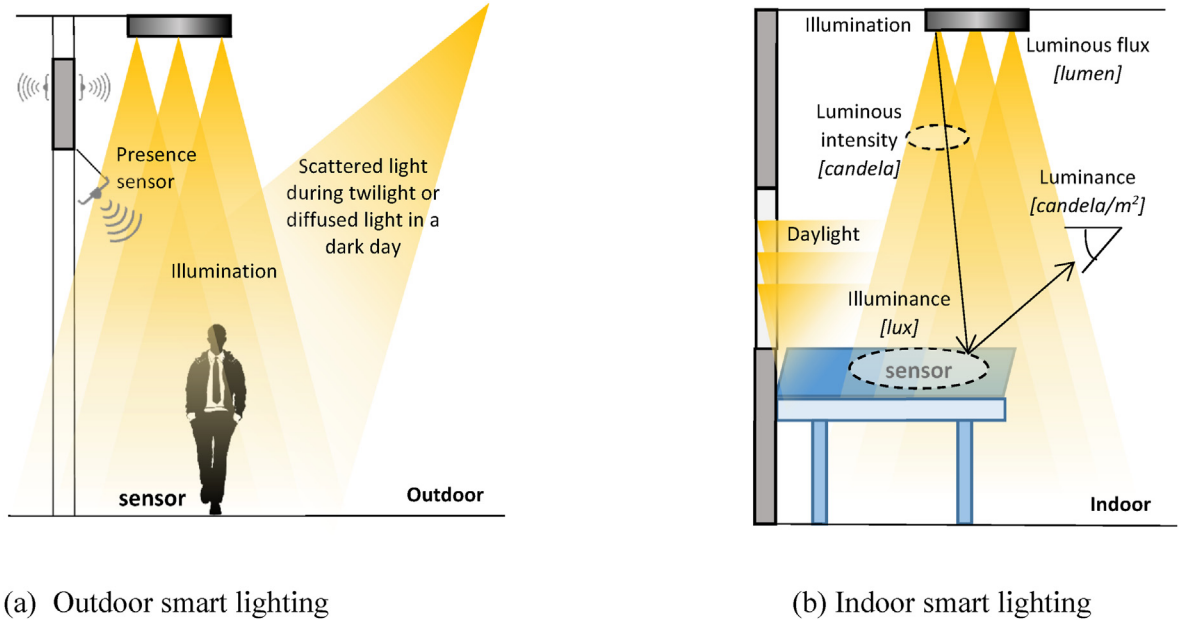
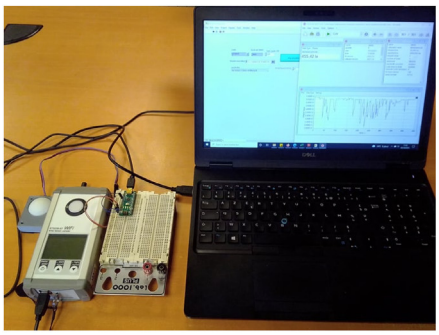
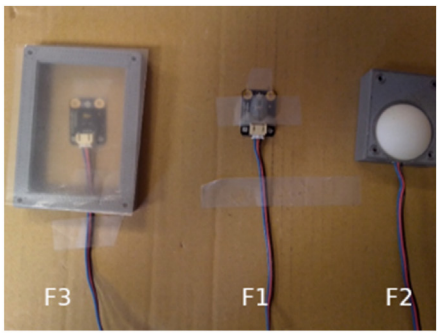


Fig. 2. Daylight harvesting in smart public lighting.



(a) Indoor measurements with the TEMT6000 photoelectric sensor and BTS-256 device



(b) Photoelectric sensor with three different filters. Physical filter one (F1) is a flat semi-transparent tape, filter two (F2) is a white semi – sphere plastic case whereas filter three (F3) is a flat semi-transparent plastic layer.

Fig. 3. Indoor and outdoor measurements with photoelectric sensor and reference device.

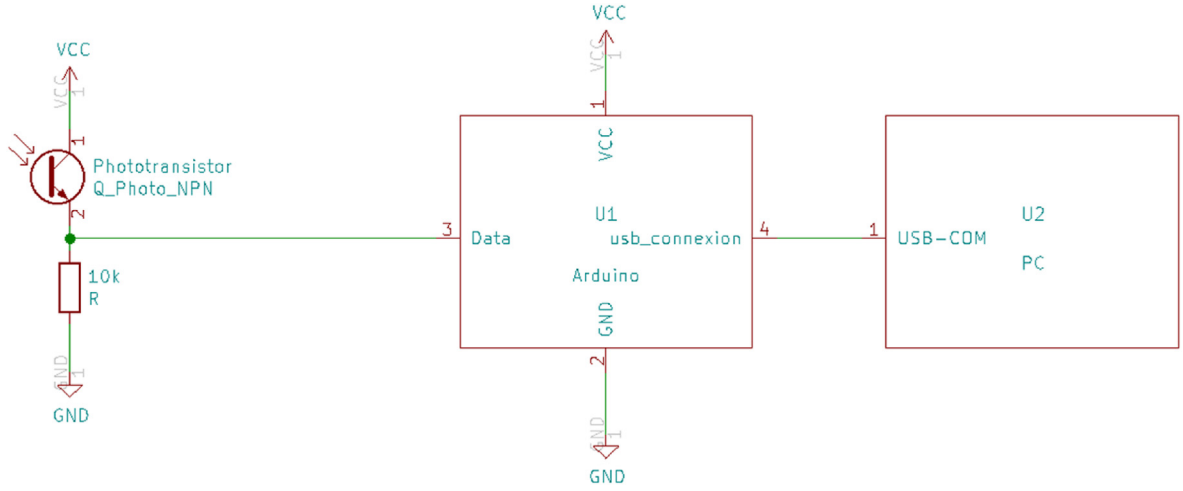


Fig. 4. Schematic of the experimental setup for photoelectric sensor validation.

material, and a semi-sphere white plastic material were tested between the light source and the PT to distribute light and prevent shadows. Data from a compact spectroradiometer device was used as a reference for the PT sensor's indoor and outdoor measurements. For outdoor measurements, the setup was placed on the ground as illustrated in Fig. 2, and for indoor measurements, the setup was positioned on a table in an office. The measurement data from the BTS256 compact spectroradiometer and the PT sensor were visualized to indicate differences at various illuminance levels.

3. Experimental setup and measurements

In this research, the Vishay TEMT6000 phototransistor was chosen for testing as a sensor for public smart lighting needs. This photoelectric sensor's collector-emitter current varies proportionally with ambient illuminance [25]. The output collector-emitter current was converted into voltage using a 10 kΩ resistor connected in series with the collector. The collector voltage was then read by an Arduino Nano, and LabView was used to log data from the sensor. Various physical filters were tested to determine the most suitable one. The experimental setups are shown in Fig. 3, and the electronic schematic is in Fig. 4.

The aim was to evaluate the performance of the photoelectric sensor for daylight harvesting purposes in outdoor smart lighting, based on illuminance values specified in regulations [6–8]. EU and Ireland standards were selected since the Interreg Smart Space pilot cities are in these regions. According to the Irish Road Lighting Standards, the ambient light levels for turning on and off luminaires are clearly defined: 35 lx and 18 lx, respectively, for high-intensity discharge lights, and 20 lx for both turning on and off LED luminaires [6]. Other regulations classify illuminance values based on ambient light levels, luminaire types, illumination environments, and the function of locations [13].

The Gigahertz-Optik BTS256 is a mobile light and color meter used with the S-BTS256 software. It can measure luminous flux, spectrum, color, and color rendering indices of individual LEDs, as well as log data. This device is utilized as a reference to validate the measurements obtained by the phototransistor. The calibration device comes with its own software for interfacing with a computer and displaying the measurements.

Experiments were conducted using the TEMT6000 photoelectric sensor with three different types of hardware filters. These experiments tested the sensor's light-sensing performance under various light levels and indoor-outdoor conditions. The filters used were: Filter one (F1), a flat semi-transparent tape layer; Filter two (F2), a white semi-sphere plastic case; and Filter three (F3), a flat semi-transparent plastic layer (Fig. 3(b)). Fig. 3(a) shows the tested phototransistor with the F2 filter, connected to an Arduino Nano and a computer. The BTS256 spectroradiometer was also connected to the same computer for data logging.

Fig. 4 shows the schematic of the measurement setup. An Arduino

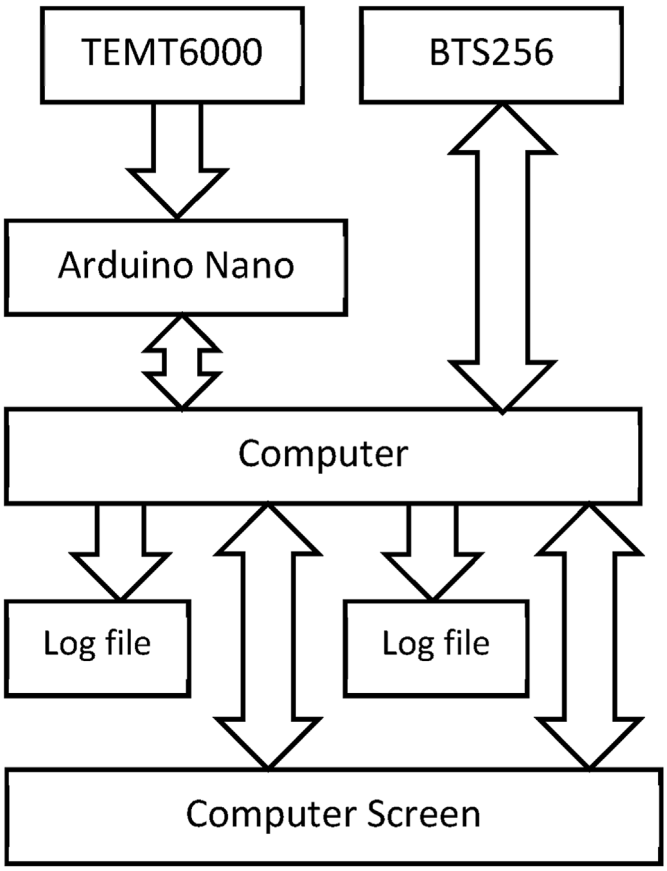


Fig. 5. Measurement block diagram.

Nano was chosen to interface the sensor signal with the computer. A wide-angle photoelectric sensor is considered more suitable for sensing illuminance as it can better compensate for differences between direct light and ambient light. The Vishay TEMT6000 phototransistor was selected because it can measure up to a ±60° half-sensitivity angle, compared to the TEPT4400 phototransistor, which measures up to a ±30° half-sensitivity angle [25,26].

For outdoor measurements, the experimental setup is placed on the ground as shown in Fig. 2. For indoor measurements, the setup is positioned on a table in the office. Both the PT sensor and the BTS256 are connected to the same computer, allowing for synchronized data logging to ensure simultaneous measurements. Fig. 5 illustrates the measurement block diagram of the experimental setup.

Fig. 6(a) shows the locations of the smart lighting and the outdoor sensor test sites. One of the luminaires at the site is depicted in Fig. 6(b).

3.1. Indoor measurements

Experiments were conducted with three different types of hardware filters implemented on the photoelectric sensor, under varying light levels and indoor-outdoor conditions. Filter one (F1) is a flat semi-transparent tape layer, filter two (F2) is a white semi-sphere plastic case, and filter three (F3) is a flat semi-transparent plastic layer (Fig. 3(b)). Table 1 presents the illuminance ranges measured by the PT with different physical filters, all using the same measurement coefficient of 11.5. The numbers in parentheses following the BTS (BiTec Sensor Luxmeter) indicate the measurement time in seconds. The number of tape layers for the F1 filter is also noted in parentheses in the PT-F1 column. Due to the very low light levels, the dark room with natural light was studied with two measurement times: 1 s and 13 s.

The SFS-EN 12461–1:2011 indoor lighting standard specifies the minimum required illuminance levels for the task area and its surroundings. The minimum illuminance levels are 30 lx for ceilings, 50 lx



(a) locations of smart public lighting



(b) One of the smart public luminaires in the location

Fig. 6. Locations of luminaires and installations.

Table 1
Variation of experiments.

Light Sources	Devices	Measurement Time (s)	PT-F1 Illuminance range (lx)	PT-F2 Illuminance range (lx)	PT-F3 Illuminance range (lx)
Dark room	BTS	1	25–1069	54–1282	47–1539
+one source	PT	1	24 - 751 (2L)	169–2288	33–1049
Lighted room	BTS(1s)	1	548–1417	507–1241	542–1470
+one source	PT	1	496 - 1272(2L)	717–1434	643–2176
Dark room	BTS	13 | 1	9 - 89 (13s)	14–110 (1s)	
+Natural light	PT	13 | 1	3 - 40 (1L) (13s)	0–7 (1s)	

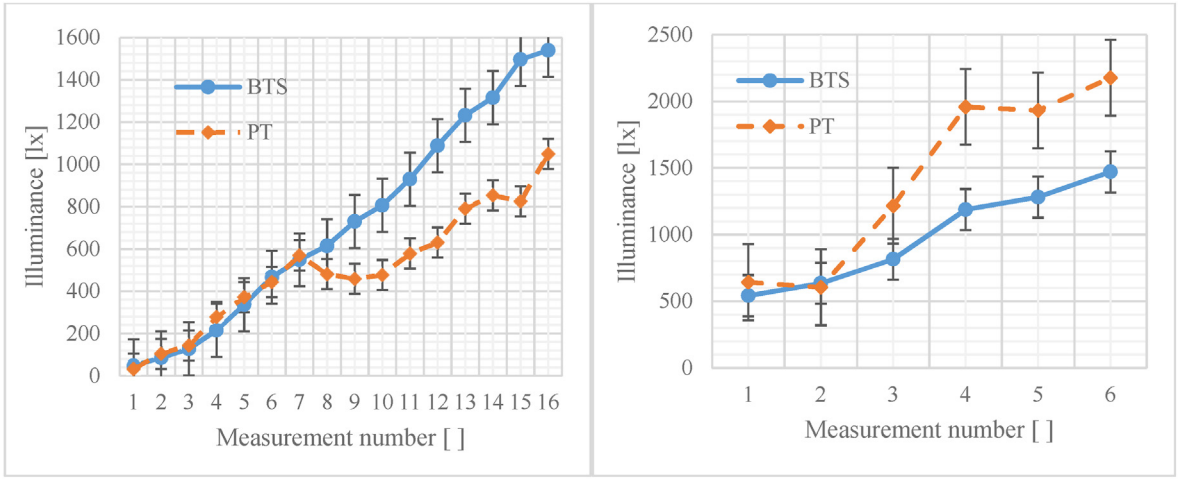


Fig. 7. Flat plastic cover (F3) indoor measurements.

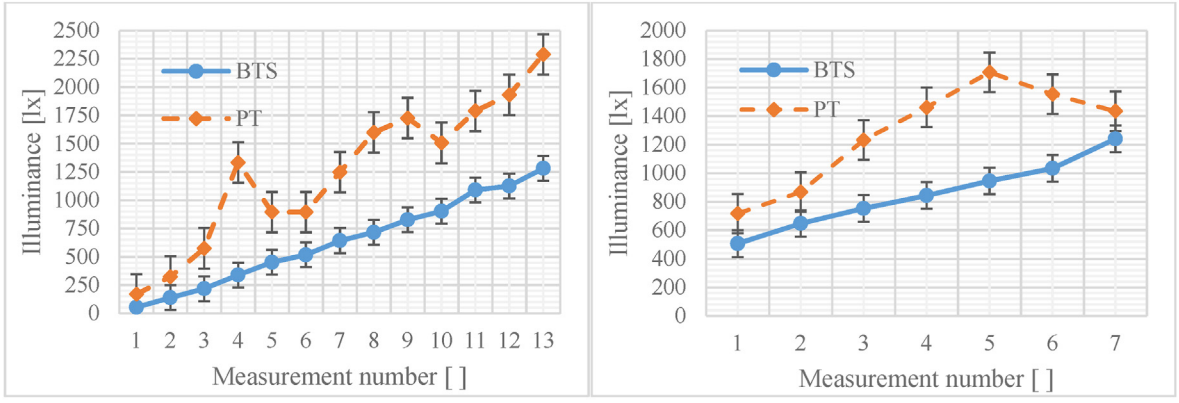


Fig. 8. Semi sphere white plastic cover (F2) indoor measurements.

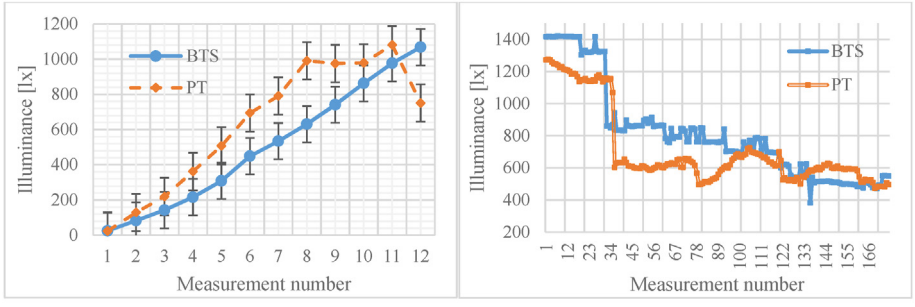


Fig. 9. Semi-transparent flat cover (F1) indoor measurements.

for walls, and 75 lx for parking areas. The minimum illuminance level is 100 lx for corridors, storage areas, and lifts. For offices, kitchens, and auditoriums, the minimum illuminance level is 500 lx. For classrooms, it is 300 lx. For precision and detailed tasks (like testing, and adjustments) the light level may even approach 1500 lux.

Measurements using different physical filters in indoor conditions are shown in Figs. 7–9. In the first stage, the PT sensor is covered with a flat plastic sheet, and the experiment is conducted indoors. Starting with the light level of a dark room (Fig. 7(a)) and then a lit room (Fig. 7(b)), the light level is varied. The PT sensor has a coefficient of 11.5, with an acquisition time of 1 s and a sampling time of 100 ms. Measured values are averaged over 1 s. The illuminance values obtained from the PT and BTS are presented in Fig. 7. PT sensor with F3 flat cover provides a linear output in illuminance level below 500 lx and can be used in indoor smart

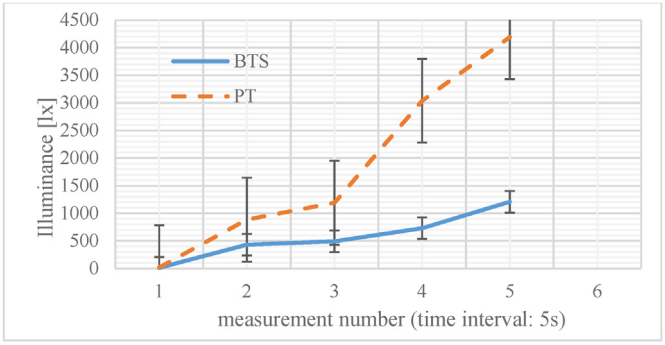


Fig. 10. Semi-sphere white plastic cover (F2) indoor measurements.

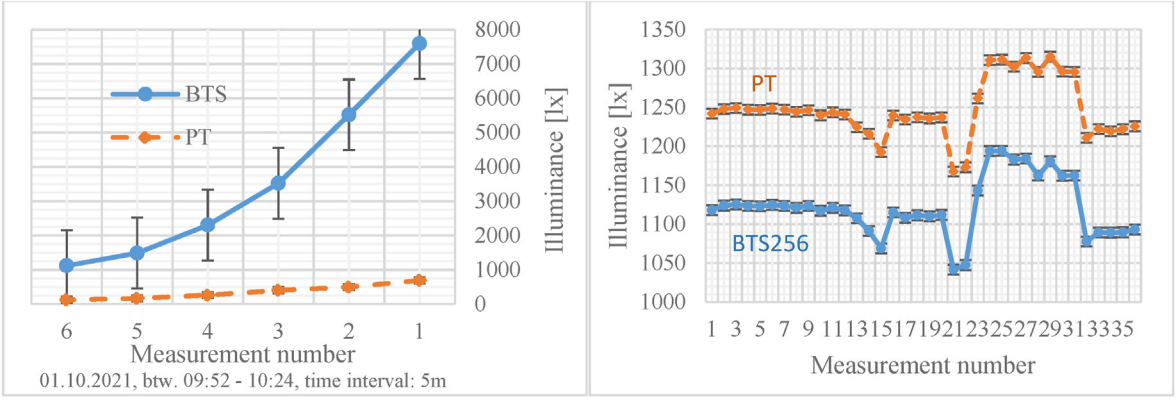
lighting applications below this level.

In the measurements shown in Fig. 8(a) and (b), the PT sensor is covered with a semi-sphere white plastic cover. The experimental setup is installed indoors. The light level is varied, starting from a dark room (Fig. 8(a)) and then a lit room (Fig. 8(b)). The PT sensor has a coefficient of 11.5, with an acquisition time of 1 s and a sampling time of 100 ms. The measured values are averaged over 1 s. For indoor experiments, the output of the PT Sensor with semi spherical cover is more stable with an initial illumination level of 500 lx. Even in this case, the output of the PT sensor may have different slopes with increasing illumination. Considering the graph in Fig. 8(b), it can be said that the PT sensor with F2 filter can be used easily in indoor smart lighting applications in which the illuminance level is below 1700 lx.

In the measurements shown in Fig. 9(a) and (b), the PT sensor is covered with a semi-transparent thin plastic tape. The light level is varied, starting from a dark room (Fig. 9(a)) and then a lit room (Fig. 9(b)). The PT sensor has a coefficient of 11.5, with an acquisition time of 1 s and a sampling time of 100 ms. The measured values are averaged over 1 s. The values obtained from the PT and BTS with increasing and decreasing illuminance levels can be seen in Fig. 9(a) and (b), respectively.

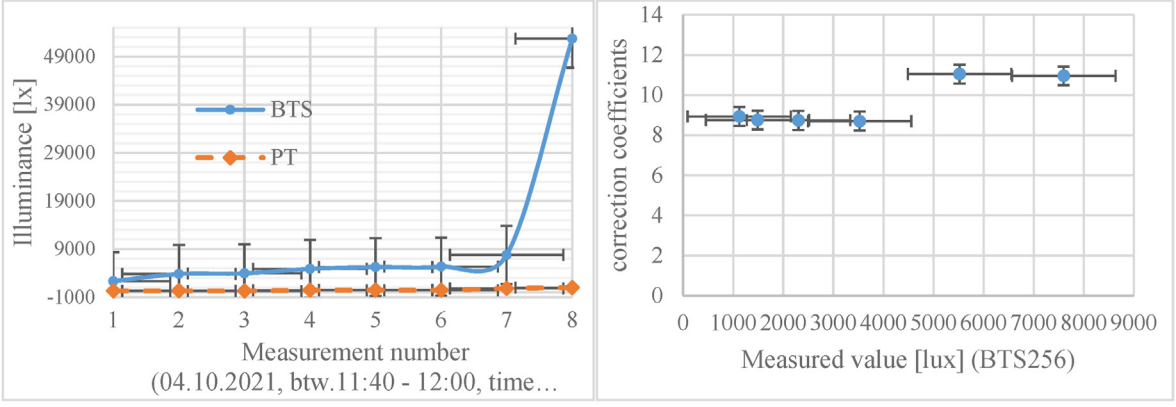
From the above results, using three types of physical filters, the curves indicate that the illuminance values for both the BTS256 and PT increase linearly up to a certain point. Beyond this point, the PT sensor becomes saturated. The BTS256 lux meter, serving as the calibration device, adjusts its posing time based on the light level. For instance, if there is insufficient light, it may take up to 5 s to measure. In brighter conditions, it automatically reduces the posing time and measures the illuminance values in less than 1 s.

In Fig. 10, the PT sensor is covered with a semi-sphere white plastic cover and installed indoors. The light level was varied, and the PT coefficient was set to 11.5. The sampling time for the measurements is 100 ms, and data was logged for 5 s. The increased number of averaged measurement values has made the PT with F2 cover more useable for the indoor smart lighting applications.



(a) PT with F2 cover under variation of light (b) PT with F2 cover around 1100lx illuminance

Fig. 11. PT with F2 cover, outdoor measurements from 9:52 a.m. to 10:24 a.m. (on October 01, 2021), the weather: cloudy, no sun.



(a) Outdoor, variation of light, sunny weather (b) Determination of two different coefficient values for look-up table

Fig. 12. PT with F2 cover, outdoor measurements from 11:40 a.m. to 12 p.m. (on October 04, 2021), sunny weather.

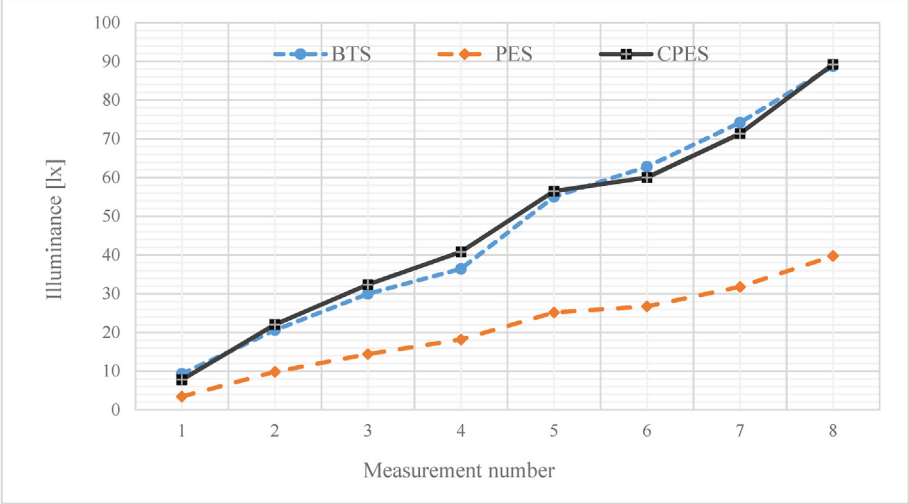


Fig. 13. Measurements between with thin semi-transparent filter between 9 lx and 90 lx.

3.2. Outdoor measurements

For outdoor measurements, illuminance data from the PT sensor was acquired every 50 ms, with the average calculated over 20 measurements per period. This average value was then calculated over 30 samples. To capture different levels of outdoor light, measurements were taken under varying shadow conditions. The PT sensor was placed in a 3D printed box and covered with a semi-sphere white plastic cover for filtering. Fig. 11(a) shows the illuminance values between 09:52 and 10:24, recorded at 5-min intervals. In Fig. 11(b), the test condition shows illuminance around 1100 lux.

Fig. 12(a) displays the measurement values from the BTS256 device and the PT sensor under a significant increase to high illuminance (under bright sunlight at noon). This test was conducted using two correction coefficients, as shown in Fig. 12(b).

Fig. 13 shows measurements ranging from 9 lx to 90 lx using the PT-F1 (PES) and a calibration device. The sampling time for the PT-F1 is 50 ms over a 13-s period, as determined by the calibration device. In these experiments, the maximum difference between the BTS and the calibrated photoelectric sensor (CPES) values is 4 lx.

4. Conclusion

In conclusion, the TEMT6000 phototransistor, when equipped with appropriate filters, demonstrates potential for use in smart public lighting systems, particularly for daylight harvesting. Indoor measurements require software filtering to address noise from fluorescent lights, while outdoor measurements generally remain stable under natural and LED lighting conditions. The sensor operates effectively within a range of 20 lx–986 lx, though it may require different correction coefficients and physical filters to handle higher light levels without saturation. Further research into physical filters is recommended for optimizing outdoor performance under bright conditions.

CRediT authorship contribution statement

Aytaç Gören: Writing – original draft, Methodology. **Fatima Khanfar:** Investigation, Data curation. **Ahmed Rachid:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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