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Assessment of Photovoltaic Panel Efficiency Under Different Spectral Characteristics of Artificial Lighting

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Abstract. The increasing use of photovoltaic (PV) systems in indoor and hybrid environments has raised the need to evaluate their performance under artificial lighting conditions. Unlike natural solar radiation, artificial light sources exhibit distinct spectral characteristics that significantly influence the energy conversion efficiency of photovoltaic panels. This paper presents an assessment of photovoltaic panel efficiency under different types of artificial lighting, with a particular focus on spectral power distribution effects. Experimental measurements were conducted using commonly applied artificial light sources, including LED, fluorescent, and incandescent lamps. The electrical output parameters of the PV panel, such as voltage, current, and power, were measured and compared under controlled illumination conditions. In parallel, the spectral characteristics of each light source were analyzed and correlated with the spectral response of the photovoltaic cell. The results indicate that photovoltaic efficiency under artificial lighting is highly dependent on spectral matching between the light source and the PV material.

Keywords. photovoltaic panels, artificial lighting, spectral characteristics, energy conversion efficiency, indoor photovoltaics.

1. Introduction

Photovoltaic systems are most often used as systems for powering buildings that do not have the ability to be connected to the power grid, water pumps, devices on roads for traffic control, or signaling. The application of small photovoltaic systems plays a great role in powering electronic devices of low consumption, such as calculators, watches, etc. It is known that data on solar cells are given for standard test conditions (AM1.5, 1000W/m^2, T=25^{0}C) for conditions when the solar cell is illuminated by sunlight. The conditions in which solar cells or small photovoltaic systems work are usually different from the conditions prescribed by standard measuring conditions. Such systems work in business premises or in the house, so that the illumination of solar cells is most often dominated by artificial light. In these applications, it is possible to mix natural light with different types of artificially emitted light. While the performance of photovoltaic panels under natural solar radiation has been extensively studied, their behavior under artificial lighting conditions remains significantly less explored. This topic has gained increasing importance with the rapid development of indoor photovoltaics, energy harvesting for low-power electronic devices, smart buildings, and Internet of Things (IoT) applications. However, the increasing use of photovoltaic systems in indoor, hybrid, and controlled environments has raised new challenges related to their performance under artificial lighting conditions. Such applications include indoor energy harvesting for low-power devices, smart buildings, industrial facilities, and laboratory-based testing and calibration setups.

Artificial light sources such as light-emitting diodes (LEDs), fluorescent lamps, and incandescent lamps exhibit spectral distributions that differ substantially from the solar spectrum. Since photovoltaic conversion efficiency is strongly dependent on the spectral match between the incident radiation and the spectral response of the PV cell, variations in light source spectra can lead to notable differences in energy conversion performance. Consequently, understanding how different artificial lighting technologies affect PV efficiency is essential for accurate system design and optimization.

This paper investigates the efficiency of small photovoltaic panels under various artificial lighting conditions with distinct spectral characteristics. The analysis focuses on comparing electrical output parameters under controlled illumination scenarios, highlighting the influence of spectral composition on energy conversion. The results aim to provide valuable insights for the development of indoor photovoltaic applications and contribute to more efficient integration of PV systems in environments dominated by artificial lighting.

2. Related Works

The performance of photovoltaic (PV) panels under artificial lighting has attracted increasing research interest, particularly in the context of indoor energy harvesting, building-integrated photovoltaics, and low-power electronic applications. Unlike solar irradiation, artificial light sources exhibit significantly different spectral distributions, intensities, and temporal characteristics, which strongly influence PV conversion efficiency.

Markvart [1] investigated the fundamental limits of photovoltaic energy harvesting under low-intensity indoor illumination, highlighting the mismatch between standard silicon PV spectral response and typical artificial light spectra. His work established a theoretical basis for evaluating PV performance in non-solar conditions.

Minnaert and Veelaert [2] analyzed the efficiency of different PV technologies under various indoor lighting conditions, including fluorescent and LED sources. Their results showed that amorphous silicon and dye-sensitized solar cells can outperform crystalline silicon panels under specific spectral distributions.

Karthaus and Fischer [3] focused on amorphous silicon solar cells under indoor lighting, demonstrating improved performance compared to crystalline silicon due to better spectral matching at lower illumination levels.

Randolph et al. [4] experimentally evaluated photovoltaic energy harvesting from LED lighting systems, emphasizing the impact of correlated color temperature (CCT) and spectral power distribution on PV output power.

In this paper [5], Park, Lee, and Kim investigate the optimization of indoor lighting spectra to improve photovoltaic (PV) energy harvesting. The authors analyze how different light spectral distributions affect the electrical output of indoor PV cells. By adjusting the spectral composition of artificial light sources, they demonstrate that it is possible to simultaneously maintain acceptable illumination quality for human comfort while increasing the energy conversion efficiency of photovoltaic devices. The results show that spectral optimization is an effective approach for enhancing indoor energy harvesting systems without increasing overall lighting power consumption.

In this paper [6], the authors analyze the performance of silicon photovoltaic modules under artificial lighting conditions. The authors compare photovoltaic performance under artificial light with standard outdoor conditions and highlight the impact of spectral mismatch and low irradiance on energy conversion. The results provide useful insights for the design and optimization of indoor photovoltaic and energy-harvesting applications.

3. Methods

The methodological approach of this study is based on a comparative assessment of photovoltaic (PV) panel efficiency under different spectral characteristics of artificial lighting sources. The analysis focuses on evaluating how variations in spectral power distribution influence the electrical performance of PV panels, particularly in terms of output power and conversion efficiency.

Several commonly used artificial light sources were considered, including light-emitting diode (LED), fluorescent, and incandescent lamps, each characterized by a distinct spectral profile. The spectral distributions of the selected light sources were obtained from manufacturer data and literature, enabling a consistent and reproducible comparison. To obtain the spectral characteristics of different sources of artificially generated light under laboratory conditions, the HPCS-320 device was used.

The mathematical model of radiation from different artificial light sources can be expressed using the following equations. The radiation spectrum of an incandescent lamp can be accurately approximated by Planck's law of black-body radiation, as the tungsten filament behaves as a thermal emitter (1):

$$E_{inc}\left(\lambda,T\right)=\frac{2\pi hc^2}{\lambda^5}\cdot\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1} \qquad (1)$$

where: λ is the wavelength [m], T is the filament temperature (typically 2500–3000 K), h is Planck's constant, c is the speed of light and k is Boltzmann's constant.

The spectrum of a fluorescent lamp is not continuous like a blackbody (as in incandescent bulbs); it's a combination of discrete spectral lines from the gas discharge (usually mercury vapor) and the phosphor coating that converts UV to visible light.

Mathematically, we can describe it as a sum of Gaussian (or Lorentzian) peaks for each emission line, plus the phosphor contribution (2):

$$I\left(\lambda\right)=\sum_i A_i \exp\left[-\frac{\left(\lambda-\lambda_i\right)^2}{2\sigma_i^2}\right]+I_{phospor}\left(\lambda\right) \qquad (2)$$

where: $I\left(\lambda\right)$ spectral power distribution (SPD) at wavelength λ [W/nm], A_i amplitude of the i-th spectral line of the gas (mercury), λ_i central wavelength of the i-th spectral line (e.g., 254 nm for mercury UV line), σ_i spectral width of that line (broadening due to pressure and other effects), $I_{phospor(\lambda)}$ broadband emission due to the phosphor coating, often modeled as a sum of smooth Gaussian functions to approximate the visible spectrum.

The mercury lines are mostly in UV (e.g., 254 nm, 365 nm, 404 nm, 436 nm, 546 nm, 578 nm).

The spectrum of a white LED is typically modeled as a superposition of multiple Gaussian components (3):

$$E_{LED}\left(\lambda\right)=E_0 \exp\left[\frac{\left(\lambda-\lambda_0\right)^2}{2\sigma^2}\right] \qquad (3)$$

where:

λ_0 is the central emission wavelength, E_0 denotes the maximum value of the spectral power distribution, σ represents the spectral bandwidth of the LED.

Unlike incandescent lamps, whose spectra follow black-body radiation laws, LED light sources exhibit discrete and tunable spectral distributions. This property enables improved spectral matching with photovoltaic panels, which is particularly important when evaluating PV efficiency under artificial lighting conditions.

The incident irradiance was normalized to comparable illuminance levels in order to isolate the effect of spectral composition from intensity-related influences.

PV panel performance was evaluated by calculating key electrical parameters such as open-circuit voltage, short-circuit current, and maximum power output under each spectral condition.

The efficiency was determined as the ratio between the electrical power generated by the panel and the incident radiant power within the effective spectral response range of the photovoltaic material. Particular attention was given to the spectral matching between the emission characteristics of artificial lighting and the spectral sensitivity of the PV panel.

To ensure consistency and reliability, the analysis was conducted under controlled conditions, assuming stable temperature and uniform illumination. The obtained results were then compared across different lighting spectra to identify trends and quantify performance deviations relative to reference conditions [7,8].

This methodological framework enables a systematic evaluation of the impact of artificial light spectral characteristics on photovoltaic efficiency and provides a basis for further experimental validation and optimization.

The short-circuit current density of a solar cell consists of two components, namely the emitter and the base components.

The spectral response of a solar cell describes its ability to convert incident radiation of different wavelengths into electrical current [7,9,13]. It represents a key parameter for assessing photovoltaic performance under artificial lighting conditions, where the spectral distribution of the light source may significantly differ from standard solar radiation [10,12].

The spectral dependence of the solar cell is commonly expressed through the spectral short-circuit current density, which quantifies the contribution of photons at a given wavelength to the generated photocurrent [10,11]. This dependence can be written as (4):

$$J_{sc}(\lambda) = q \cdot \Phi(\lambda) \cdot E_{QE}(\lambda) \tag{4}$$

$J_{sc}(\lambda)$ is the spectral short-circuit current density [A/m²·nm], q is the elementary charge, $\Phi(\lambda)$ is the incident photon flux density [photons/m²·s·nm], and $E_{QE}(\lambda)$ is the external quantum efficiency of the solar cell.

Alternatively, the spectral behavior of the solar cell can be described using the spectral responsivity (5):

$$S_R(\lambda) = \frac{J_{SC}(\lambda)}{P_{opt}(\lambda)} \tag{5}$$

$S_R(\lambda)$, defined as the ratio between the generated current density and the incident optical power at a given wavelength:

The relationship between spectral responsivity and external quantum efficiency is given by (6):

$$E_{QE}(\lambda) = \frac{h \cdot c}{q \cdot \lambda} S_R(\lambda) \tag{6}$$

These expressions provide a theoretical basis for evaluating the spectral matching between artificial light sources and photovoltaic devices which is essential for accurately assessing photovoltaic efficiency under different spectral characteristics of artificial lighting.

4. Experimental Results

The experimental setup included incandescent, LED, and fluorescent light sources, an HPCS-320 spectroradiometer, and a silicon photovoltaic module. Spectral power distributions were measured under controlled laboratory conditions and normalized for comparison. PV electrical parameters were recorded under identical illumination conditions, enabling assessment of spectral matching effects on photovoltaic performance. Figure 1 shows the spectral characteristics of an incandescent light source used in the experimental study, obtained using the HPCS-320 device.

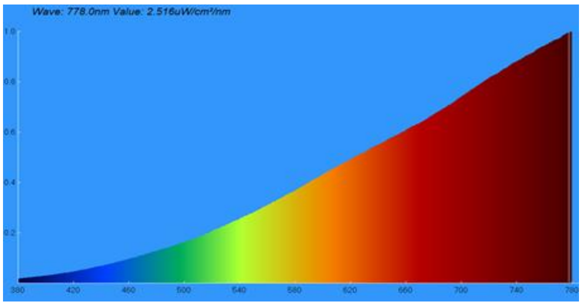

Fig.1. The spectral characteristics of a 100 W incandescent light source

The spectral characteristic shown in the figure 1. corresponds to an incandescent light source. The spectrum is continuous over the visible range and shows a gradual increase in intensity toward longer wavelengths, with the highest values in the red and near-infrared region. This behavior is typical of thermal radiation from a heated filament and follows the general shape of a blackbody spectrum. As a result, a significant portion of the emitted energy lies outside the most efficient range for visible illumination, indicating low luminous efficiency but strong emission at longer wavelengths.

Figures 2 and 3 show the spectral characteristics of the fluorescent light source and the LED light source, respectively.

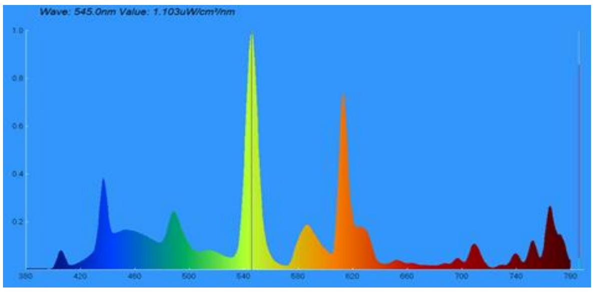

Fig.2. The spectral characteristics of a 25W fluorescent light source

The spectral characteristic of the fluorescent light source shown in the figure 2 is non-continuous and consists of several pronounced narrow peaks superimposed on a lower broadband background. The dominant emission peak appears around 545 nm, corresponding to a strong mercury emission line in the green region of the spectrum. Additional peaks are visible in the blue and red regions, resulting from both mercury vapor discharge and phosphor re-emission. This line-dominated spectrum is characteristic of fluorescent lamps and leads to relatively high luminous efficacy, but with a spectral distribution that differs significantly from natural daylight. The spectral characteristic of the LED light source shown in Figure 3 consists of a broad, smooth emission band with a clear maximum around 600 nm, located in the yellow–orange region of the spectrum.

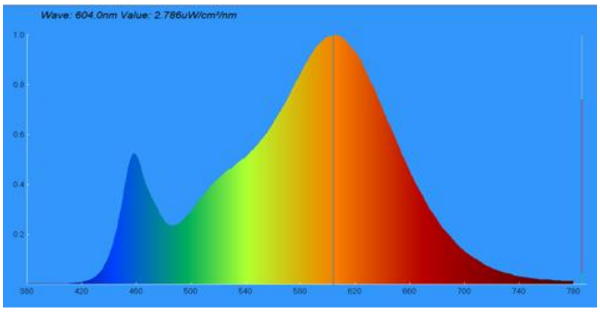

Fig.3 The spectral characteristics of a 15W LED light source

A smaller peak in the blue region is also visible, corresponding to the primary blue LED chip used to excite the phosphor layer [15]. The broad emission in the green to red wavelength range results from phosphor down-conversion, which produces white light. Compared to fluorescent lamps, the LED spectrum is more continuous, leading to improved color rendering and higher energy efficiency [10,14].

For the experimental analysis, three artificial light sources with approximately the same luminous flux of 1600 lm were selected in order to ensure comparable illumination conditions. Although the emitted light levels are similar, the electrical power ratings of the sources differ significantly. This clearly indicates variations in luminous efficacy and highlights the different efficiencies of electrical-to-optical energy conversion among the considered lighting technologies [16]. For the experiment, a small photovoltaic module with an output voltage of 5 V, a maximum current of 75 mA, and a power of 0.375 W was utilized. Figure 4 shows the spectral response of the photovoltaic module.

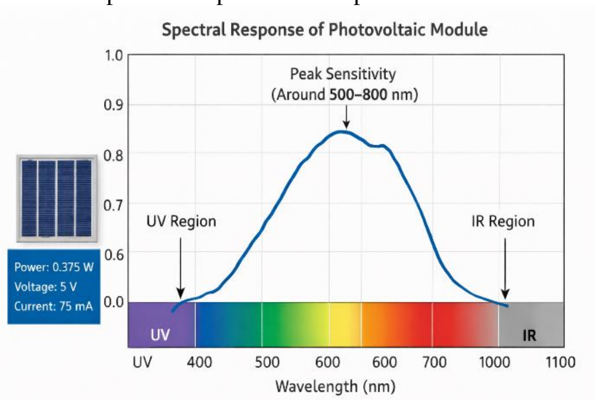

Fig. 4 Spectral Response of Photovoltaic Module

The equipment shown in Figure 5 was used for the experimental investigations.

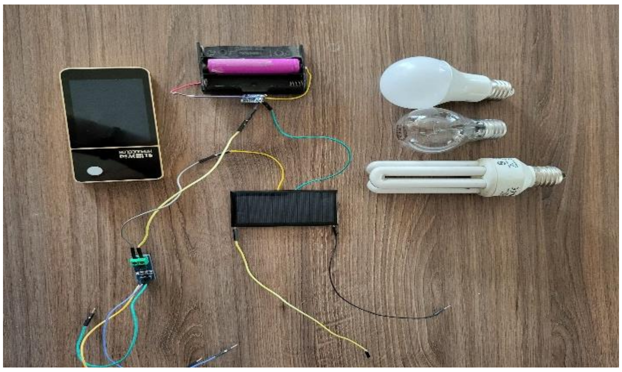
Fig. 5 Equipment for experimental research

The electrical output power of the photovoltaic module was calculated as the product of the measured voltage and current. Since the incident optical power was not directly measured, a relative efficiency was defined by normalizing the output power to its maximum value for each light source (7).

$$\eta = \frac{P}{P_{\max}} \cdot 100\% \qquad (7)$$

where: $P_{\max}$ is the maximum measured power for a given light source (at a distance of 10 cm).

Table I shows the measured output voltage of the photovoltaic module under different artificial light sources.

Table I. - The measured output voltage of the photovoltaic module

Distance (cm)	LED (V)	Fluorescent (V)	Incandescent (V)
10	3.83	2.47	4.15
20	2.88	1.77	4.11
30	2.65	1.44	4.00
40	2.47	1.20	3.81
50	2.46	1.09	3.60
150	1.15	0.90	2.47

Table II shows the measured output current of the photovoltaic module under different artificial light sources.

Table II. - The measured output current of the photovoltaic module

Distance (cm)	LED (mA)	Fluorescent (mA)	Incandescent (mA)
10	0.89	0.25	0.98
20	0.80	0.14	0.97
30	0.63	0.10	0.91
40	0.48	0.07	0.87
50	0.27	0.04	0.18
150	0.07	0.01	0.46

The measurement distances (10, 20, 30, 40, 50, and 150 cm) were selected to represent typical indoor illumination scenarios, ranging from close-proximity light sources to ceiling-mounted lighting conditions. This approach enables the evaluation of both high irradiance and low irradiance regimes commonly encountered in indoor photovoltaic energy harvesting applications.

Figure 6 shows the variation of the photovoltaic module output power as a function of the distance from different artificial light sources.

The incandescent lamp provides the highest output power due to its broad spectral content, while the LED and fluorescent sources exhibit a more pronounced power drop with increasing distance.

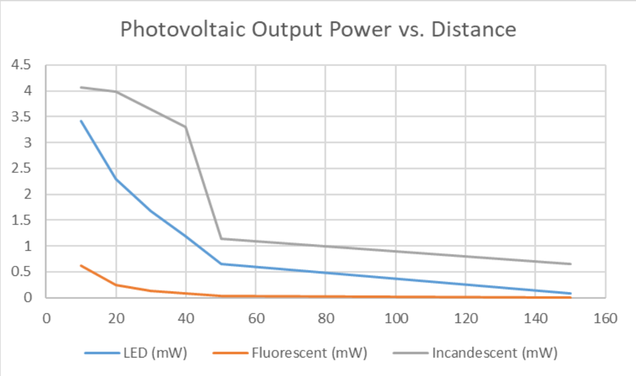

Fig. 6 The variation of the photovoltaic module output power as a function of the distance

5. Discussion

The observed differences in photovoltaic output power among the tested light sources can be primarily attributed to their distinct spectral power distributions. The incandescent lamp exhibits a broad and continuous spectrum with a high contribution in the red and near-infrared region, which overlaps well with the spectral response of the silicon photovoltaic module, resulting in the highest measured output power.

In contrast, the LED source, characterized by a narrower emission spectrum, provides moderate power levels, while the fluorescent lamp shows the lowest output power due to its discontinuous spectrum with limited overlap with the photovoltaic module's spectral sensitivity.

These results confirm that, in indoor photovoltaic applications, the spectral compatibility between the light source and the photovoltaic device plays a more dominant role than the nominal luminous flux alone.

6. Conclusion

This study assessed the effect of artificial light sources with different spectral characteristics on the energy conversion efficiency of a small photovoltaic module. The results demonstrate that spectral alignment with the PV cell's response significantly enhances efficiency, with LED illumination outperforming fluorescent and incandescent sources due to its spectrum closely matching the module's sensitivity.

The main advantage of this approach is the ability to optimize indoor PV performance using tailored light sources, while a key limitation lies in the inherent dependency of efficiency on both spectrum and illuminance, which may vary in practical settings.

Potential applications include indoor energy harvesting for low-power devices, integration of PV modules in smart lighting systems, and optimization of hybrid lighting-PV installations.

These findings highlight the importance of considering spectral composition in addition to intensity when evaluating PV performance under artificial lighting.

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