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Three types of photovoltaic technologies under different artificial indoor light sources

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ABSTRACT

Photovoltaics as a technology contributing to the implementation of the idea of sustainable development is constantly developing, and its applications can be extended to indoor conditions, where artificial light can be converted in order to power remote electrical devices. The objective of this work was to investigate and evaluate the performance of three types of commercial mini modules such as monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and dye-sensitized (DSSC) under the illumination of incandescent, LED and halogen lamps which varied in power, luminous flux and color temperature. The light sources were characterized by irradiance spectra and the current-voltage characteristics of the illuminated modules were measured. For all studied cases, the generated electric power per unit area was determined and discussed. The findings indicate the potential of DSSCs especially in the area of matching the light source intensity spectrum to the absorption range of the sensitizing dye. DSSC mini module accompanied by artificial LED lighting is suggested as the most energy saving prospective solution.

Keywords: indoor photovoltaics, artificial light source, Internet of Things, IoT, DSSC.

INTRODUCTION

The currently observed development of alternative energy sources is a necessity conditioned by the increasing demand for energy, as well as the growth of the world's population. Nowadays, global electricity consumption rises due to industrial activities, but also due to the growing interest in high-performance computers used by the constantly developing artificial intelligence and cryptocurrency mining. For example, in 2023, the electricity usage from bitcoin mining was 121 TWh, and in 2025, the annual consumption is estimated as 171 TWh, which is higher than many countries need per year. During the past 10 years the share of alternative energy sources in global electricity generation has grown significantly. In years 2010–2023 the installed capacity of photovoltaics increased 40 times [IEA 2024 World Energy Outlook] and photovoltaics together with wind energy accounted for 75% of the rise in power from alternative energy sources (Figure 1). Although the most common photovoltaic systems are large plants or individual rooftop installations, more and more often photovoltaic (PV) modules are mounted in other places e.g. on the surface of water reservoirs, above agricultural fields, or integrated with buildings and hybrid vehicles. Prospective development of Internet of Things (IoT) and smart houses based on autonomic appliances will also require new solutions in electric power supply, which can be provided by photovoltaic cells working inside the buildings under ambient light. The idea of usage artificial lighting can be broadened also to outdoor application of photovoltaics, enabling "recycling" or "recovery" of light in metropolises where there is an excess of light, considered harmful "light pollution".

Ambient light can include illumination from a variety of light sources, including: LEDs, halogen lamps, cold cathode fluorescent lamps and incandescent bulbs. Each of the light sources has its own irradiance spectrum [Biswas et al., 2020]; therefore in order to improve the performance of

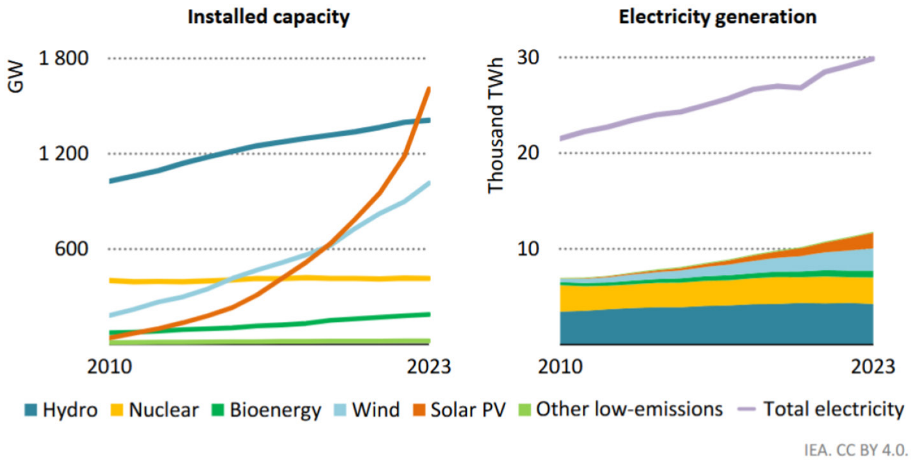


Figure 1. Global installed capacity and electric energy generation from alternative energy sources [IEA 2024 World Energy Outlook]

photocells for indoor purposes, the spectral response of the materials responsible for absorption of light in the given type of cell should match the spectrum of the lamp.

In the literature, most articles focus on the use of fluorescent light and investigation of small laboratory experimental photocells modified by introducing new materials or changes in their structure [Lee et al., 2017]. Despite the fact that silicon solar cells have undisputed first place in the production of modules and installed power in the world [Photovoltaics Report 2024], research on the performance of solar cells in artificial light, developed in recent years, is mainly devoted to the representatives of the third generation of laboratory photovoltaic devices such as dye sensitized solar cells and perovskite solar cells. Among these types of photocells, dye sensitized solar cells (DSSCs), which are photoelectrochemical devices, are particularly attractive due to their well-known ability to convert low-intensity scattered light [Saud et al., 2024; Iman et al., 2024]. Other exceptional features such as lightness, flexibility and small size facilitate the integration of DSSCs into objects of various shapes and even textiles. Optimization of photovoltaic performance of dye-sensitized cells is obtained by introducing new types of dyes [Hosseinnezhad et al., 2024; Ren et al., 2022]. Semitransparency and diversity of colors expand the opportunities of application in BIPV as smart windows, wireless communication and other devices (e.g. cameras, medical equipment, keyboards, and sensors) integrated with portable charging. Currently, the main manufacturers of DSSC modules are G24 and RICOH offering DSSCs with solid electrolyte, which ensures the durability of the cells operating in a wide temperature range from -30 to 60 °C [Ricoh, 2025] and continuous growth of market is predicted [DSSC Market Report, 2018]. There are also numerous companies that are globally recognized for their contribution to the DSSC materials supply chain, such as Dynamo, Greatcell and Solaronix.

In laboratory tests, high power conversion efficiency of 34% was achieved for the dye cells sensitized with XY1 and L1 dyes due to suppression of recombination at the photoanode. Adjustment of the cell spectral response and use of a copper-based electrolyte influenced such good performance under fluorescent illumination [Michaels et al., 2020]. The same type of the electrolyte and co-sensitization with XY1b and Y123 dyes led to power of 101.2 uW/cm^2 obtained by DSSCs under indoor lighting [Cao et al., 2018].

In indoor applications, perovskite photovoltaic cells based on the material containing a triple anion (I, Br, Cl) in the structure showed excellent efficiency of 36.2% under fluorescent light as a result of the reduction of the trap states [Cheng et al., 2019]. Furthermore, the solar cells made from III-V semiconductors, known for high efficiency under standard test conditions (STC), exhibit promising indoor parameters. An example is GaAs photocell that achieved PCE of 22% with a double-junction structure under LED illumination due to very good spectral matching [Moon et al., 2020]. However, the high production cost of III-V photocells constitute a serious barrier, considering the fact that indoor photovoltaics is intended to be an alternative to replacing batteries.

The goal of this work was to evaluate how much electric power can be delivered by photovoltaic mini modules under ambient lighting conditions of varying spectrum and intensity. In literature, small dye-sensitized and perovskite laboratory cells, as well as experimental DSSC mini module were tested under fluorescent light [Hinsch et al., 2012]. Most studies have focused on optimizing the cell structure and properties of materials used in experimental photocells. There are no such investigations conducted to date on commercial full-size modules or mini modules illuminated by different types of bulbs, however the wider indoor applications of photovoltaics require known and tested technology. Comprehensive literature review [Biswas et al., 2020; Yan et al., 2020], demonstrated the performance of second generation (e.g. thin film a-Si, CIGS, GaAs) and third generation photovoltaic technologies represented by dye sensitized, organic and perovskite single laboratory cells in various types of indoor lighting applications. However, commercial monocrystalline, polycrystalline Si or dye-sensitized modules were not considered, only numerical model for DSSC under fluorescent and LED illumination was developed [Rahmatian et al., 2024].

In this work the investigations were carried in the context of practical application of photovoltaic mini modules of different technologies under variety of indoor light. Three types of commercial mini modules such as monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and dye-sensitized (DSSC) were tested under the illumination of incandescent, LED and halogen lamps which varied in power and luminous flux. This work presents a novel approach which adds practical knowledge on the performance of mini modules available on the market under artificial indoor light. The presented investigation can navigate future producers of home appliances powered by photovoltaics and users to match proper PV technology and type of lamp.

METHODS

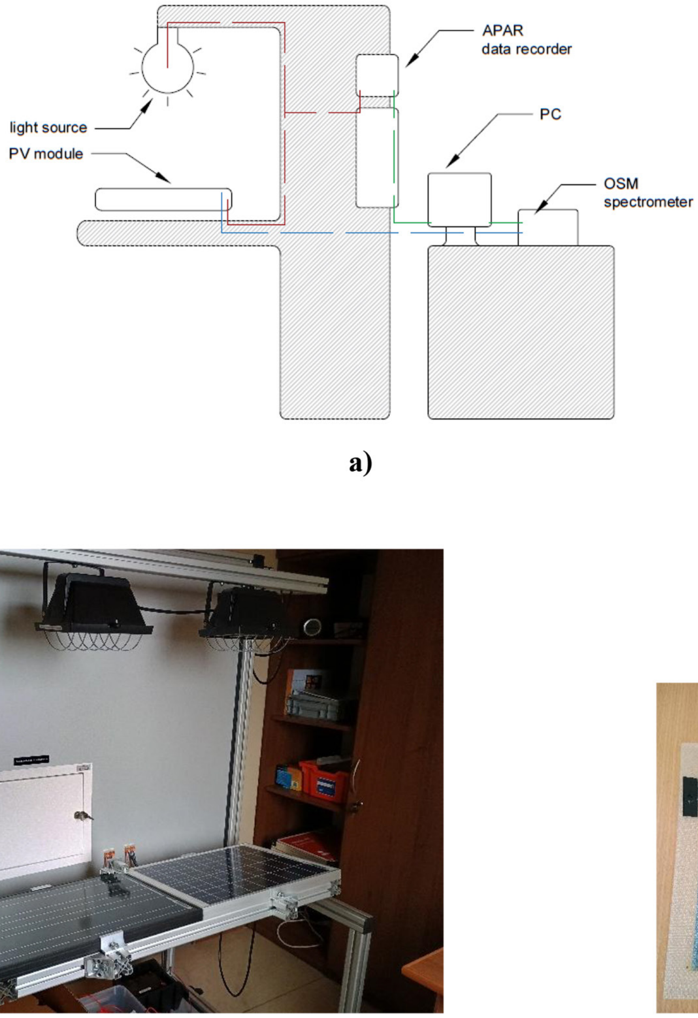
For the lightening of photovoltaic modules in indoor experiments a variety of popular commercial sources were used: incandescent light bulb, LED and halogen. Three bulbs of each type with different parameters were used. The power, temperature, luminous flux and illuminance of each light source are presented in Table 1. The technical parameters of mono-Si, poly-Si and dye-sensitized commercial photovoltaic mini modules are shown in Table 2. In order to register the current-voltage characteristics of selected photovoltaic mini modules and lighting parameters, all components

Table 1. Parameters of light sources

Type of lighting	Symbol	Temperature [K]	Power [W]	Luminous flux [lm]	Illuminance [lux]
Incandescent	I1	2700	40	420	540
	I2		60	630	1280
	I3		150	2160	4300
LED	L1		4.9	470	1266
	L2	6500	9.6	1060	3780
	L3	4000	11	1055	3380
Halogen	H1	2700	20	235	96
	H2		33	460	191
	H3		60	975	489

Table 2. Nominal parameters of PV modules

Photovoltaic module parameters provided by the manufacturers				Unit
Type	Monocrystalline	Polycrystalline	Dye-sensitized	[-]
Model	Cl020-12mb	Cl20-12p	G24	
External dimensions	0.34 × 0.45		0.2 × 0.15	[m]
Active area	0.09		0.02	[m^2]
Power density	222		25	[W/m^2]
Maximum power	20		0.5	[W]



a)

b) c)

Figure 2. (a) Scheme of experimental setup; (b) photo of experimental setup with monocrystalline and polycrystalline silicon modules, head of light sensor between them and lamps; (c) dye-sensitized module

were assembled according to the diagram shown in Figure 2a. Figure 2b and 2c present photos of experimental setup and tested photovoltaic modules. More photos of the equipment are showed in Supplemetary Information. The main part of the experimental setup was MGS EZSO-62+ station equipped with APAR AR207 data recorder. All measurement series were performed in a darkroom, at the same controlled temperature and were repeated 3 times. The light source was located 25 cm above the geometric center of each module.

The measurements of current and voltage were performed automatically by the recorder, only the resistance on the additionally connected MCP BXR-07 decade resistor had to be changed manually. The resolution of measurements was 0.0001 mA for the current, 0.0001 V for the voltage and 1 Ω for the resistance. The range of resistance change was from 0 Ω to 11 kΩ, the measurement range was 1 A for current and 60 V for voltage. The accuracy of measurements was 0.001 mA for the current, 0.001 V for the voltage and 1 Ω for the resistance. The illuminance of each light source was measured with a SANOPAN L-100 luxmeter equipped with a G.L-100 measuring head at 4 corner points of each module and in its center in order to obtain the most reliable average data. Each investigated mini module was mounted in horizontal position. The measuring range of luxmeter was 0.001 lx to 300 klx, accuracy class A, overall accuracy of measurements is ≤2.5%. The spectral distribution of light was determined using NEWPORT OSM2-400DUV-U spectrophotometer at a distance of 0 cm from the lighting source. Spectral range of the spectrophotometer was 200–1100 nm, resolution 1 nm.

RESULTS

Indoor light sources

Each type of light source used in experiments has different irradiance spectrum, depicted in Figure 3–5. Incandescent and halogen bulbs exhibit similar spectra showing a gradual increase of irradiance from 450–500 nm towards longer wavelengths up to 800 nm. The spectrum of LED bulb differs due to two maxima present at 450 nm and 600 nm and a wider distribution of energy than for other two lamps. It is worth emphasizing that, the growth of power of the bulbs, and in consequence luminous flux and illuminance (Table 1), always results in higher irradiance.

Photovoltaic modules under artificial light

The performance of Si monocrystalline, polycrystalline and dye-sensitized photovoltaic modules was investigated under three types of indoor lighting provided by three different bulbs of each type. The current-voltage characteristics are presented in Figure 6–8. All the figures show the following trend: the higher the power of the bulb of given type, the better photovoltaic performance assessed in terms of open circuit voltage U_{OC}, short circuit current I_{SC} and in consequence the obtained power P_{mpp}. The significant spread of U_{OC} values is visible for the bulbs of different power. The discussion of the delivered photovoltaic parameters can be based on the detailed data

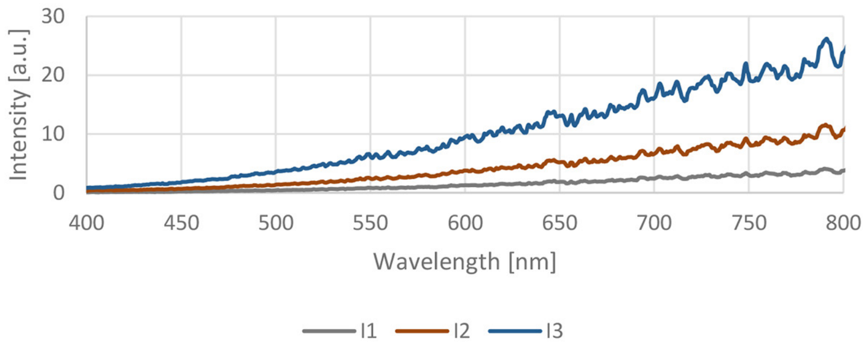


Figure 3. Irradiance spectra of incandescent bulbs

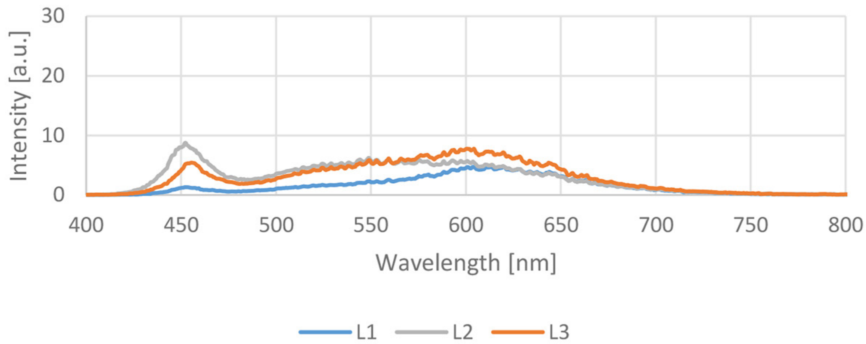


Figure 4. Irradiance spectra of LED bulbs

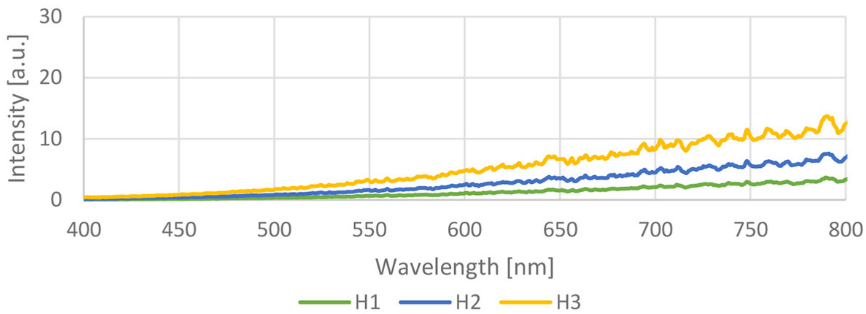


Figure 5. Irradiance spectra of halogen light

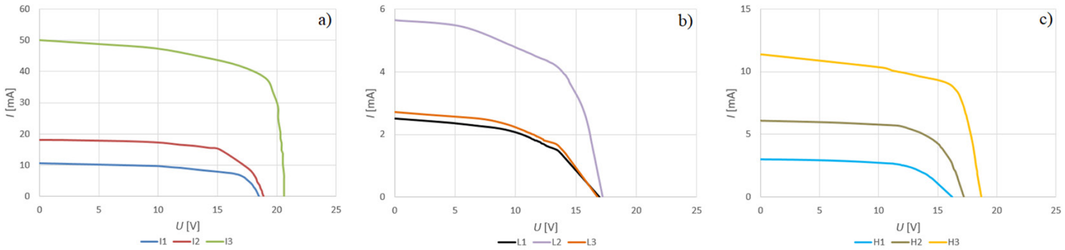


Figure 6. *I-U* characteristics of mono-Si mini module under illumination of (a) incandescent (I1, I2, I3) light, (b) LED (L1, L2, L3) and (c) halogen (H1, H2, H3)

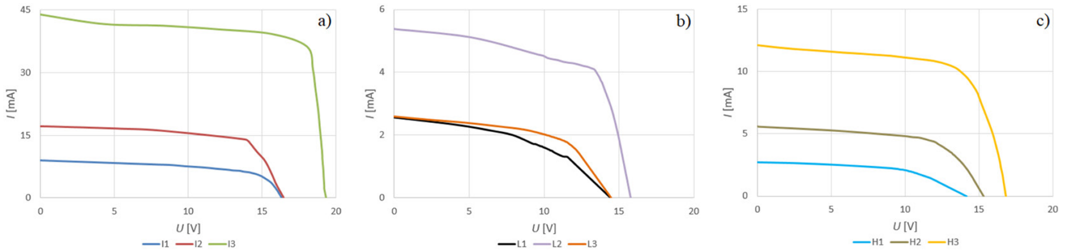


Figure 7. *I-U* characteristics of poly-Si mini module under illumination of a) incandescent (I1, I2, I3) light, b) LED (L1, L2, L3) and c) halogen (H1, H2, H3)

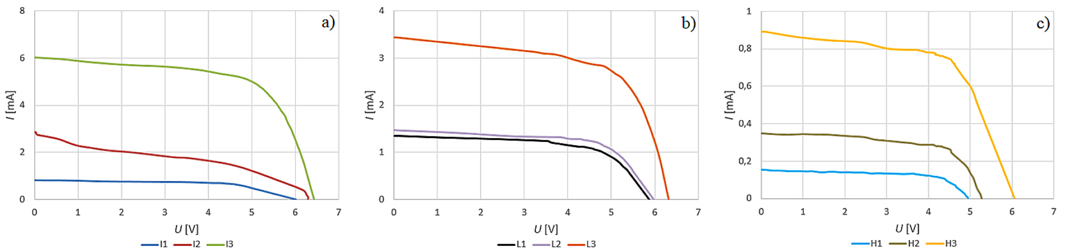


Figure 8. *I-U* characteristics of DSSC mini module under illumination of a) incandescent (I1, I2, I3) light, b) LED (L1, L2, L3) and c) halogen (H1, H2, H3)

Table 3. Parameters of mono-Si mini module under indoor light

Type of lighting	Symbol	Parameters of mono-Si mini module		
		Isc [mA]	*Uoc* [V]	P_{mpp} [mW]
Inscandescent	I1	10.57	18.48	119.41
	I2	18.17	18.86	228.76
	I3	50.11	20.60	722.0
LED	L1	2.50	16.90	21.11
	L2	2.71	16.76	22.87
	L3	5.64	17.22	55.89
Halogen	H1	3.02	16.24	30.69
	H2	6.11	17.23	69.54
	H3	11.35	18.69	143.7

presented in Tables 3–5. Monocrystalline module provides the best results for the incandescent bulb: U_{OC} values are in the range of 18.48–20.6 V and maximum power reaches 722 mW. The usage of LED and halogen leads to similar results, however power of 143.7 mW was obtained with 60 W halogen bulb (H3). A similar result was obtained with 40 W incandescent bulb (I1)

Table 4. Parameters of poly-Si mini module under indoor light

Type of lighting	Symbol	Parameters of poly-Si mini module		
		Isc [mA]	*Uoc* [V]	*Pmpp* [mW]
Inscandescent	I1	9.02	16.30	87.49
	I2	16.45	17.12	193.48
	I3	43.9	19.33	653.05
LED	L1	2.57	14.42	16.12
	L2	2.60	14.46	20.74
	L3	5.38	15.78	52.19
Halogen	H1	2.73	14.15	20.84
	H2	5.62	15.32	52.57
	H3	12.10	16.83	138.06

providing 119.41 mW. Poly-Si works a little bit worse since maximum of 653 mW was obtained under the illumination of I3 having power of 150 W. The power of 138.06 mW was achieved under illumination H3 bulb. LED, which power is in the range of 4.9–11 W and is the lowest among the tested bulbs, provides the lowest parameters.

The DSSC module, characterized by the nominal power much lower than both silicon modules, provides the lowest values of maximum power, from 0.49 mW to 25.1 mW, for H1 and I3 bulb respectively. Comparison of the results obtained for DSSC under LED and halogen illumination indicates that L1 LED provides higher power than I1 incandescent light, which is exceptional among the investigated modules. The performance of mono Si an poly Si is the best under incandescent and the worst under LED illumination. However, DSSC works relatively well under LED, but halogen light leads to the lowest produced power.

The described dependences are also reflected by the values of power (Figure 9) delivered by the investigated three types of modules. The results depicted in Figure 9 are expressed in W/m^2 because it allows for a module comparison from a practical point of view, when determining the electric power demand of a device that can be supplied. Dye sensitized solar modules differ significantly from silicon modules in terms of both power and photoactive area. The photoactive area of DSSC module is 4.5 times lower and power is 40 times lower than for Si modules. In spite of that, the performance of DSSC is the best under illumination of LED light in comparison to other PV technologies. This result indicates that LED characteristic spectrum, exhibiting maximum at 450 nm and the other broader band is at 550–650 nm, is an appropriate source of light for DDSC technology.

DISCUSSION

The comparison of the shape of the presented irradiance spectra of incandescent, LED and halogen bulbs with well-known solar light spectrum shows significant mismatch which indicates that

Table 5. Parameters of DSSC mini module under indoor light

Type of lighting	Symbol	Parameters of DSSC mini module		
		Isc [mA]	*Uoc* [V]	*Pmpp* [mW]
Inscandescent	I1	0.83	6.02	3.02
	I2	2.87	6.30	6.63
	I3	5.92	6.44	25.10
LED	L1	1.35	5.87	4.95
	L2	1.47	5.98	5.66
	L3	3.44	6.32	13.67
Halogen	H1	0.15	4.95	0.49
	H2	0.34	5.28	1.21
	H3	0.89	6.07	3.37

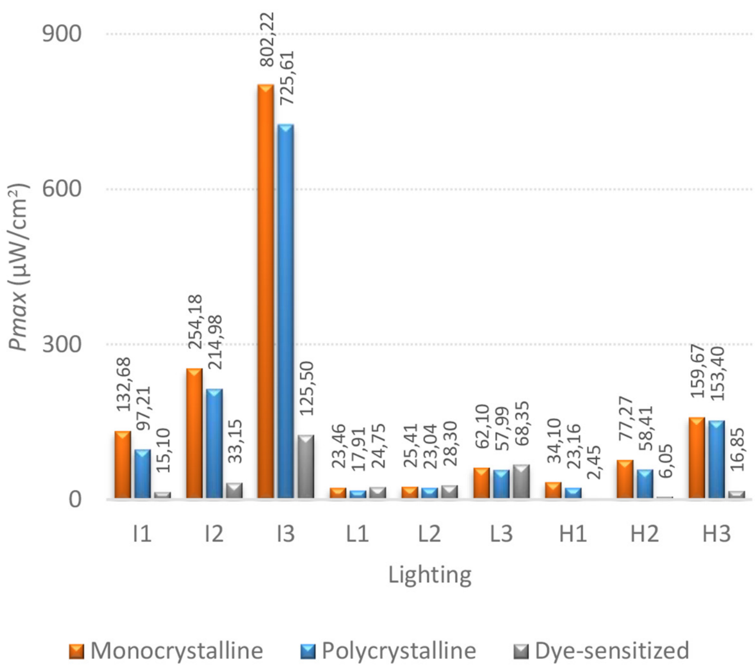


Figure 9. Electric power produced, divided by the active area of mini modules

artificial light sources differ from natural white light to a considerable extend. Moreover, outdoor solar light is characterized by much higher illuminance flux from 10 000–20 000 lux under rainy or cloudy conditions up to 100 000 lux in direct sunlight [Aslam et al., 2020].

Although all investigated types of photovoltaic modules provide the highest electric power under illumination of incandescent light with highest power of 150 W, the results obtained for DSSC under LED light draws attention. The power of 68.35 μW/cm^2 produced by DSSC under L3 LED bulb characterized by 11 W power is four times higher than 16.85 μW/cm^2 obtained under illumination of an H3 halogen of 60 W. Therefore it is worth emphasizing that matching between spectrum of light source and absorption spectrum of photoactive material of the cell is crucial. The light absorption range, which differs in terms of positions of absorption bands, in dye cells depends on the type of sensitizing dye. The exemplary ranges of light wavelength absorption of selected dyes are: 200–400 nm exhibited by natural dye from Chrysanthemum [Leite et al., 2023], 500–600 nm or 500–700 nm for BODIPY dyes [Yildiz et al., 2019], 400–550 nm for fisetin and luteolin [Zdyb and Krawczyk, 2019], 400–600 nm for alizarin and phenylfluorone [Zdyb and Krawczak, 2021; Krawczak et al., 2025]. Due to this differences co-sensitization with mixed dyes is a successful strategy leading to efficiency of DSSC exceeding 10% [Badawy et al., 2024; Alenazi et al., 2024]. In the context of operation of DSSC under artificial light, the first attempts to match dye absorption range of selected dyes and bulbs emission profiles were recently reported in literature in the research focused on small laboratory dye cells [Salerno et al., 2025].

The values of power generated by the DSCC mini module presented in this work are in the range of values obtained for single DSSC laboratory cells under fluorescent light: 47–36.6 μW/cm^2 at 500 lux [Cao et al., 2018], 318.2 μW/cm^2 [Cheng et al., 2019] and 19 μW/cm^2 for 200 lux to 103.1 μW/cm^2 at 1000 lux with different sensitizers [Michaels et al., 2020]. Regarding other PV technologies belonging to the third generation the following results were achieved: 278.7 μW/cm^2 for OPV cells and 154.6–310 μW/cm^2 at 1000 lux for perovskite cells [Cheng et al., 2019].

CONCLUSIONS

The determination of photovoltaic parameters of mini modules under different types of ambient light allowed assessing the investigated technologies in terms of usefulness under indoor conditions. The presented research indicates that mono-Si and poly-Si mini modules work best under incandescent and the worst under LED lighting. Performance of DSSC is relatively good under LED, and the lowest produced power was obtained with a halogen lamp. Although the illumination by incandescent bulbs leads to satisfactory results of photovoltaic performance, electric power consumption of incandescent bulbs is the highest.

The approach with a combination of the DSSC technology with LED lighting is prospectively the most interesting direction indicated based on the presented research. In the context of indoor applications, DSSC offers important beneficial features such as inexpensive assembly procedure, flexibility and light weight of modules. The advantage of DSSC comparing to traditional Si technology is also the possibility of selecting the sensitizing dye in order to match absorption spectrum of a dye to irradiance spectrum of LED. Tailoring of the absorption spectrum by choosing a proper dye or mix of dyes in order to enhance the harvesting of light emitted by LED can be an important topic of future research. Moreover, LED bulbs compare favorably with other tested bulbs due to low power consumption and relatively high illuminance. The strategy based on an energy-saving LED bulb illuminating DSSC mini module can supply energy for low power consumption devices such as sensors and other small portable equipment in a smart house.

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