



Silicon Solar Cells for Indoor Photovoltaic Applications

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ARTICLE INFO	ABSTRACT
Article history: Received 4 July 2025 Received in revised form 5 August 2025 Accepted 10 August 2025 Available online 21 August 2025 Keywords: indoor photovoltaics; silicon solar cells; low-light energy harvesting; artificial lighting; IoT power	The rapid adoption of Internet of Things (IoT) devices, smart home appliances, and wireless electronics has created a growing demand for energy sources that can operate reliably and sustainably indoors. While traditional batteries provide a temporary solution, they are constrained by limited lifespans and the need for frequent maintenance or replacement. Indoor photovoltaics (IPVs), which convert artificial indoor lighting into electrical energy, have emerged as a compelling alternative. Among the materials explored for IPVs, silicon stands out due to its commercial maturity and excellent long-term stability. Although originally developed for outdoor use, silicon solar cells are now being adapted to function under low-intensity and narrow-spectrum indoor lighting. This review examines the performance, advantages, and challenges of silicon solar cells in indoor environments. It highlights recent innovations in materials and device architectures, explores real-world applications, and discusses future directions that can enhance efficiency and integration. Despite certain limitations such as spectral mismatch and form factor constraints, silicon remains a promising platform for enabling maintenance-free, sustainable energy harvesting in indoor settings.

1. Introduction

The proliferation of smart electronics and the Internet of Things (IoT) has fundamentally changed how energy is consumed and managed in indoor environments [1]. From smart thermostats and wearable health monitors to wireless sensor networks, the demand for continuous and autonomous power sources has increased exponentially. Traditional battery-powered solutions, while effective, pose significant limitations, including finite lifespans, maintenance requirements, and environmental concerns related to disposal and recycling. This has led researchers and technologists to explore alternative energy sources that can sustainably support indoor electronic devices.

One of the most promising approaches is the use of photovoltaic (PV) technology, which has diverse applications in building-integrated PV (BIPV), portable and off-grid power systems, space satellites, agrivoltaics, and bifacial panel designs [2-6]. A specific branch of this technology is indoor

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PV (IPVs), which harvest energy from ambient artificial light sources such as LED and fluorescent lamps[7]. Figure 1 shows some of the real-life applications of IPVs available in market.

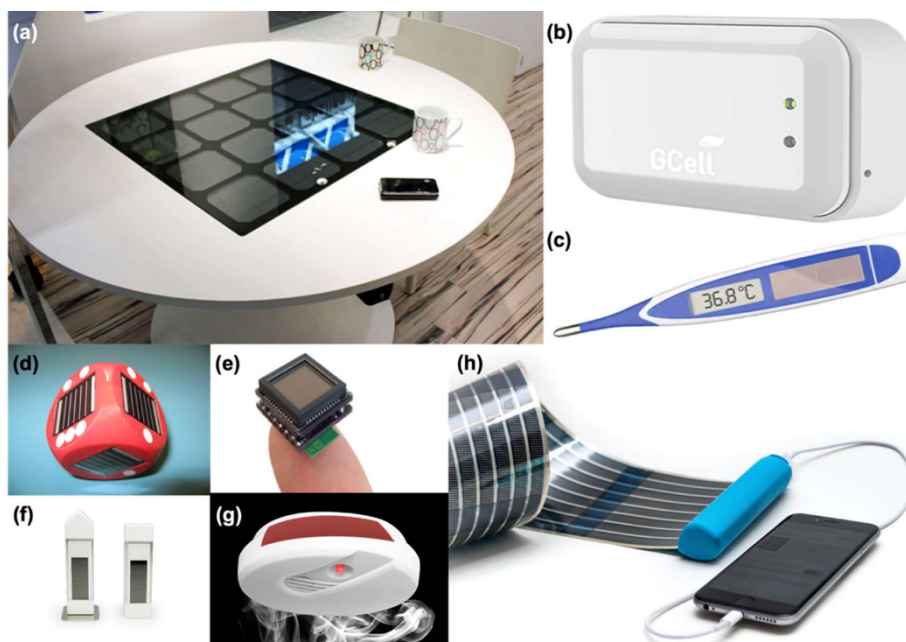


Fig. 1. Example of IPV application in real-world. (a) Inductive charging table by Panasonic, (b) iBeacon device by GCell, (c) Digital thermometer by Geratherm Medical AG, (d) Wireless solar-powered IoT dice, (e) Power management IC with 1 cm² PV module for wireless sensor nodes, (f) Battery-less wireless temperature and humidity sensor by Afriso, (g) Smoke detector with integrated dye-sensitized solar cell by 3GSolar, (h) HeLi-on flexible solar charger using organic PV technology by InfinityPV. Figure compilation reproduced from [8]. Copyright (2024), Elsevier

IPVs are distinguished from traditional solar PVs by their operating conditions. Unlike outdoor environments, where sunlight is intense and broadband with a spectrum reaching into the near-infrared, indoor lighting is generally of lower intensity and narrower in spectral distribution, often concentrated in the visible range (400-700 nm). Additionally, indoor lighting conditions are more stable and predictable compared to the variable and sometimes harsh conditions outdoors. This difference in operating environment necessitates careful consideration of material properties, device architecture, and electronic integration for photovoltaic systems intended for indoor use.

Among the variety of PV technologies including dye-sensitized solar cells (DSSCs) [9], organic PV (OPVs) [10-17], and perovskite solar cells (PSCs) [18-22], silicon remains a material of interest due to its established commercial infrastructure, abundance, and exceptional stability [23]. Although traditionally optimized for outdoor use under the AM1.5G solar spectrum, silicon solar cells are now being adapted for indoor lighting conditions[24]. These adaptations include physical restructuring, optical optimization, and system-level integration strategies.

Despite not being spectrally ideal for indoor conditions, silicon solar cells have several inherent advantages. They are already mass-produced at a low cost, benefit from decades of research and development, and offer long-term operational stability [25]. Furthermore, they are available in miniaturized or customized modules that can be seamlessly integrated into indoor environments[26]. These factors make silicon solar cells a compelling option for enabling sustainable, maintenance-free indoor energy harvesting.

This review explores the viability and current advancements of silicon solar cells for indoor applications. It begins with an examination of their performance under artificial lighting conditions,

followed by a discussion of key advantages and limitations. Recent innovations and practical use cases of indoor silicon photovoltaics are then highlighted. Finally, the review outlines future research directions and technological developments that could further improve their applicability and efficiency.

2. Silicon Solar Cell Performance Indoors

The performance of silicon solar cells in indoor environments is markedly different from their behavior under outdoor sunlight. This discrepancy arises primarily due to the spectral and intensity differences between natural sunlight and artificial indoor lighting. Silicon, with its indirect bandgap of approximately 1.1 eV, is optimized for broadband solar radiation that includes significant near-infrared content [27]. In contrast, artificial light sources such as LEDs and fluorescent lamps emit a narrower spectrum of light, primarily in the visible range [28]. Moreover, the intensity of indoor light is typically one to two orders of magnitude lower than sunlight, with typical values ranging from 100 to 1000 lux, corresponding to irradiance levels of 10 to 100 $\mu\text{W}/\text{cm}^2$ [29]. Figure 2 illustrates the AM1.5 solar spectrum compared to representative spectra of common indoor light sources, including cool LEDs and fluorescent lamps. Unlike the AM1.5 spectrum, which spans from ultraviolet to infrared, artificial light sources lack the infrared component and exhibit much narrower spectral widths. These fundamental differences in spectral distribution and intensity pose unique challenges for photovoltaic technologies designed for indoor environments.

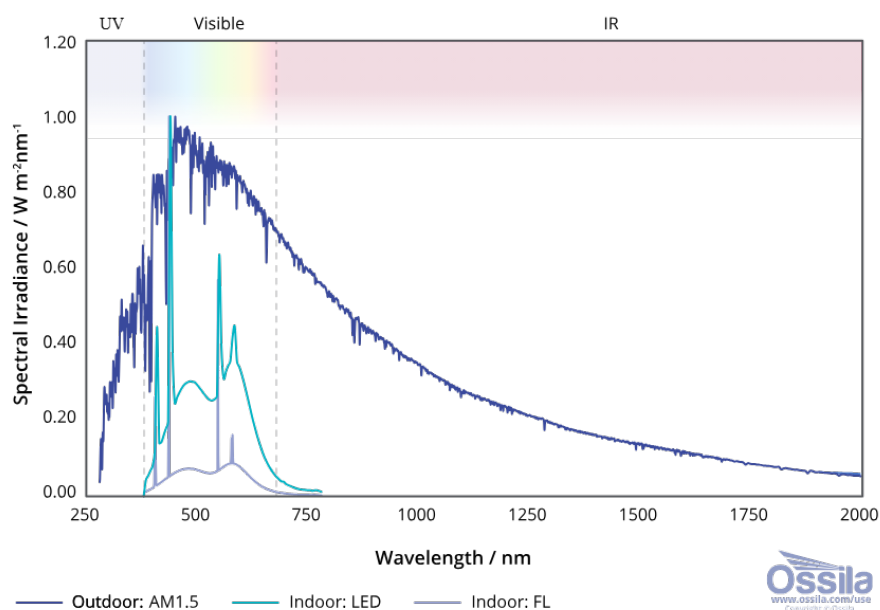


Fig. 2. Comparison of indoor light spectra (cool LED and typical fluorescent) with the standard AM1.5G solar spectrum (dark blue). Image sources: <https://www.ossila.com>

Under such low-light conditions, several aspects of silicon solar cell behavior change. The open-circuit voltage (V_{oc}) decreases logarithmically with light intensity, leading to significantly lower voltages indoors. The fill factor (FF) and short-circuit current density (J_{sc}) are also adversely affected by parasitic resistances and recombination losses, which become more pronounced at lower light levels [1]. As a result, the overall power conversion efficiency (PCE) of silicon cells drops significantly indoors [30]. Despite these challenges, recent advancements have shown the IPV performance of crystalline and amorphous silicon solar cell as tabulated in Table 1. The table compiles recent research

on the IPV performance of crystalline silicon (c-Si) and amorphous silicon (a-Si) solar cells under various artificial lighting conditions. Across the reported studies, c-Si cells often achieve superior J_{sc} , particularly under high illuminance (for example 126.0 mA/cm² at 1000 lx in 2020 and 119.2 mA/cm² at 1000 lx in 2023), which contributes to competitive PCEs even in artificial lighting. The table also shows a clear upward trend in PCE for both technologies over the years, with recent studies reporting notable efficiency improvements such as 16.3% for a-Si and 15.5% for c-Si in 2023, indicating material and design advancements tailored for indoor applications. Differences in active area, Voc, FF, and light source type further highlight the importance of optimising device architecture and testing conditions to maximise indoor energy harvesting performance.

Table 1

IPVs performance of crystalline (c) and amorphous (a) of silicon solar cells

Year	Devices	Light Type/ Illuminance (lx)	Voc (V)	Jsc (mA/cm ²)	FF (%)	PCE (%)	Area (cm ²)	Ref
2015	c-Si	LED / 890	0.43	0.12	71	9.65	1	[31]
	a-Si	LED / 200	2.46	14.2	57.2	7.51	3.18	[32]
2016	a-Si	FL / 1000	2.9	20	-	3.68	3.49	[33]
2017	a-Si	LED / 1000	0.63	83.85	58	-	3.60	[34]
2018	c-Si	LED / 1000	0.33	102.29	-	-	1.93	[35]
2019	a-Si	LED / 200	0.63	21.8	68	12.2	1.04	[36]
2020	c-Si	LED / 1000	0.43	126.0	67.0	12.5	4	[37]
2021	c-Si	LED / 1000	1.18	41.73	59	9.3	48	[38]
2023	c-Si	LED / 1000	0.519	119.2	71.3	15.5	4	[39]
	a-Si	LED / 1000	0.71	89.4	73.1	16.3	7.65	

3. Advantages and Limitations

Silicon solar cells offer a unique blend of advantages that make them a valuable contender in the field of indoor photovoltaics. Foremost among these is their commercial maturity [40]. Silicon-based PV technologies benefit from decades of development, extensive global manufacturing infrastructure, and economies of scale that significantly reduce cost per watt. Their widespread availability and compatibility with standard semiconductor processing techniques also facilitate rapid prototyping and customization for various form factors. Another critical advantage is durability. Silicon solar cells are highly stable under ambient conditions, with proven lifespans of 25 years in outdoor installations. Indoors, where temperature fluctuations, humidity, and UV exposure are minimized, their operational stability is expected to be even higher. This makes them ideal for long-term applications such as wireless sensor nodes, building automation systems, and energy-harvesting consumer electronics.

However, several limitations restrict the indoor performance of silicon solar cells. Chief among these is spectral mismatch. Silicon's bandgap and absorption profile are best suited for the full solar spectrum, which includes significant near-infrared components. Indoor light sources, particularly LEDs and compact fluorescents, emit narrower spectra concentrated in the visible region. This limits the number of photons silicon can absorb and convert efficiently. Another issue is reduced electrical performance under low-light conditions. As light intensity drops, the Voc, Jsc and FF of silicon cells decline disproportionately, leading to lower power output. Form factor is also a challenge. Conventional c-Si modules are rigid and thick, making them less suited for applications requiring flexibility or ultra-compact design. Although thin-film silicon and micro-scale cell arrays address this partially, they often come at the cost of reduced efficiency or higher fabrication complexity.

While silicon solar cells have many strengths such as mature technology, environmental safety, and excellent durability, they must overcome challenges related to spectral mismatch, low-light electrical losses, and integration constraints to fully realize their potential in indoor applications.

4. Future Direction

One promising direction is spectral optimization. To bridge the spectral mismatch between silicon and indoor light sources, researchers are exploring the use of optical coatings, photonic structures, and surface texturing that enhance light absorption in the visible range. These techniques aim to minimize reflectance and increase the number of photons absorbed per unit area, thus improving efficiency under low-intensity, narrow-spectrum lighting.

Tandem cell architectures represent another exciting avenue. By stacking a high-bandgap top cell such as perovskite above a silicon bottom cell, the overall device can harvest a broader range of the visible spectrum, enhancing performance under indoor lighting.

Materials engineering efforts are also focused on developing low-cost, ultra-thin silicon wafers and flexible substrates that maintain reasonable efficiency while enabling new form factors. Roll-to-roll processing and heterojunction designs are being explored to support lightweight and mechanically compliant modules suitable for integration into wearables, packaging, and non-planar surfaces.

Finally, sustainability considerations are gaining prominence. As demand grows for eco-friendly electronics, silicon's abundance, non-toxicity, and recyclability become even more attractive. Research is increasingly oriented toward circular design, where modules are designed for easy disassembly and material recovery, minimizing their environmental footprint.

5. Conclusion

Silicon solar cells, though historically tailored for outdoor photovoltaic applications, are steadily proving their relevance in indoor environments. Their resilience, cost-effectiveness, and environmental safety profile give them a strong foundation upon which enhancements can be made for indoor use. As this review has shown, silicon solar cells are already achieving indoor power conversion efficiencies of 3–16%. While not ideally suited to the spectral characteristics of artificial indoor lighting, ongoing innovations in optical engineering, tandem structures, and low-light power management are bridging the gap between traditional silicon cell design and the requirements of indoor energy harvesting.

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Conflict of Interest Statement

The author declares that there are no conflicts of interest related to the publication of this manuscript.

Author Contributions Statement

S.S. was responsible for the conceptualization, validation, formal analysis, investigation, resources, visualization, original draft preparation, review and editing of the manuscript, and project administration.

Data Availability Statement

No datasets were generated or analysed during the current study.

Ethics Statement

This study did not involve human participants, animals, or sensitive data, and therefore did not require ethical approval.

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