Performance Evaluation of Carbon-Based Printed Perovskite Solar Cells under Low-Light Intensity Conditions

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The use of photovoltaics (PVs) to harvest energy inside modern building environments has great potential for energizing a wide range of futuristic self-powered electronic devices, Internet of Things (IoT), and sensors using available ambient light. Among the various PV technologies, hole-conductor-free carbon-based printable perovskite solar cells (CPSCs) have attracted significant interest, owing to their impressive PV performance under standard full sunlight conditions, robust stability, and printable fabrication methods. Nevertheless, their ability to harvest indoor light has been rarely explored. Here we report PV performance characterization of these printable CPSCs, and a systematic comparison of their PV performance under commonly available fluorescent (FL) and light-emitting diode (LED)-based lamps at various low light intensities that replicate standard indoor environmental conditions. To consolidate the proven stability of these CPSCs, the results of one stability test standardized as ISO-S-D-1, which supports the motivation of their possible deployment under mild indoor lighting conditions are presented. The effective functioning of these CPSCs is also demonstrated for energizing an electrical node as evidence of their potential to be used as an alternative light-harvesting solution for the targeted futuristic IoT-based ecosystem. These results greatly support the goal of developing all printed and sustainable IoT devices with robust performance stability.

1. Introduction

Energy harvesting technologies collect various forms of ambient energies such as heat, light, or vibrations to generate electricity at micro scales.[1,2] Provided that the wasted energy dissipated in the environment is ubiquitous, energy harvesters present the potential to be self-sustaining with an ideal infinite functioning lifetime. Therefore, they have been considered a potential alternative to the traditional battery-based energy solutions presently enforced to energize electronic consumer goods, the Internet of Things (IoT), or other distributed electronic-based ecosystems.[3,4]

Since many of these electronic devices are typically located inside buildings, there is potential for energizing them via integrating photovoltaics (PVs) that can harvest abundantly available ambient indoor light energy from LED, halogen, and FL lamps or other types of light sources. This promising approach can be used to achieve sustainability within portable electronic devices, as well as in advanced-distributed electronic environments.[1,3,5-9]

Keeping this motivation in mind, established silicon (Si) solar cell-based PV technologies have initially been deployed to harvest ambient light energy for energizing various low-powered electronic appliances such as calculators, digital thermometers, and electronic clocks.[10] However, the low power conversion efficiency under low-light conditions, combined with high production costs have limited their widespread use in indoor applications.[7,8,11]

In contrast to Si-based PVs, third-generation-based solar cell technologies such as organic solar cells (OSC) or dye-sensitized solar cells (DSSC) have shown striking performance with higher conversion efficiencies when tested under indoor light conditions.[12-19]

Similar to these third-generation-based PV technologies, the escalating conversion efficiencies of perovskite solar cells (PSCs) under standard illumination conditions[20,21] consequently motivated research labs worldwide to also examine their PV performance under various ambient light intensities.[22-26] As expected, the striking conversion efficiencies of PSCs achieved in recent years (Table 1) under these ambient light intensity conditions provide preliminary evidence for considering them as another potential light-harvesting solution for energizing...
Table 1. PV performance of traditional perovskite solar cell configurations reported under various low-light-intensity conditions.

| Device structure | Configuration | Type of lamp | Intensity [Lux] | P_in [μW/cm²] | Active area [cm²] | PCE | Reference |
|------------------|---------------|--------------|----------------|----------------|------------------|-----|-----------|
| Glass/ITO/PEDOT:PSS/PVK/PCBM/TmPyPB/Ag | Planar p-i-n | Philips 6500 K T5 FL lamp | 1000 | 300 | 0.05 | 27.4 | [29] |
| Glass/ITO/TiO2/PVK/Spiro-OMeTAD/Au | Mesoporous n-i-p | CFL (Lxerman, Class A) | 400 | – | 0.12 | 25.4 | [30] |
| Glass/ITO/SnO2/MgO/PVK/Spiro-OMeTAD/Au | Planar n-i-p | White Osram Parathom | 400 | – | 0.1 | 26.9 | [31] |
| Glass/FTO/NiO/PVK/PC61BM/[BMIM]BF4 | | Classic P25 light-emitting diode (LED) lamp | 1000 | 278.7 | 0.09 | 35.2 | [32] |
| Glass/ITO/SnO2/PVK/Spiro-OMeTAD/Au (modification layer)/Ag | Planar n-i-p | Osram L18W/827 FL lamp | 1000 | 280 | 0.06 | 34.5 | [33] |
| Glass/ITO/SnO2/PVK/Spiro-OMeTAD/Au | Planar n-i-p | Philips T5 6400 K FL lamp | 500–2000 | – | 0.1 | 27 | [34] |
| Glass/ITO/MeO2/TPTPA/PVK/C60/TmPyPB/Au | Planar p-i-n | Philips T2 15 W/E27 FL lamp | 1000 | 275.4 | 0.36 | 31.8 | [35] |
| Glass/ITO/TiO2/PVK/TAPA-8BPNT/Au | Mesoporous n-i-p | | – | – | – | 0.30 | [36] |
| Glass/ITO/TiO2/PVK/Spiro-OMeTAD/Au | Planar n-i-p | LED lamp (McSciene, Suwon, South Korea) | 1000 | 280 | 0.06 | 34.5 | [37] |
| Glass/ITO/PTAA/PVK/PEACI (surface passivation) /ICBA/C60/BUP/CB | Planar p-i-n | PAK-LED-TS-4WF-865 (3000 K) | 1000 | 279.6 | 0.105 | 35.6 | [38] |
| Glass/ITO/SnO2/ZnO/PVK/Spiro-OMeTAD/Au | Planar n-i-p | White LED lamp (6500 K) | 1000 | 309.8 | 0.1 | 37.2 | [39] |
| Glass/ITO/TiO2/PVK/CH3O-PEABr (surface passivation)/Spiro-OMeTAD/Au | Planar n-i-p | DYSON, warm-white | 824.5 | 301.6 | 0.08 | 40.1 | [40] |
| Glass/ITO/SnO2/SnO2/PVK/PDTDA/T | Planar n-i-p | BLD-100 white LED (5000 K) (Bunkoukeiki Co., Ltd) | 200 | 60 | 0.09 | 34.2 | [41] |
| Glass/ITO/PTAA/P3HT/PVK/C60/BCP/Cu | Planar p-i-n | Warm-white LED lamp (2700 K) | 1000 | – | 0.02 | 39.2 | [42] |

*Solar modules were also produced and reported under low-intensity light conditions in these reports.

advanced self-powered electronic devices, IoT, electrical nodes and sensor-based applications.[23,27,28]

Nevertheless, the PV performance of these PSCs is frequently reported with very small active areas in their traditional mesoporous or planar n-i-p configuration,[44–45] or inverted planar p-i-n-based device configurations,[46,47] which have also been frequently criticized due to their poor long-term PV performance stability.[48–52]

Therefore, despite revealing high performance under various ambient light intensity conditions, these traditional device configurations raise concerns about achieving the stable and infinite functioning lifetime expected for futuristic self-powered electronic devices, IoT, and sensor applications.[6,53–55]

Contrary to these traditional configurations of PSC technology, hole-conductor-free carbon-based triple mesoscopic printable perovskite solar cells (CPSCs)[56,57] offer unique opportunities including low cost of fabrication with established scalable methods such as screen- or inkjet-based printing techniques.[58,59]

Moreover, their robust and long-term PV operational stability outperforms other reported traditional device configurations of PSC technology, as frequently proven under various simulated and natural environmental conditions since they were first reported.[36,60,61] These characteristics make CPSCs an ideal candidate to be used as potential energy harvesters for the aforementioned robust and self-sustaining targeted applications.

Interestingly, despite their robust stability and frequently proven high performance under standard illumination conditions, only a few reports mention their brief PV performance analysis under low light intensity conditions.[62,63] This calls for more independent experimental evidence to reach a systematic and consistent consensus for projecting this promising device configuration of PSC technology as a reliable and alternative energy harvesting solution, and how it compares to other emerging PV technologies or unstable PSC device configurations reported in the past decade.

To this end, we characterize the fundamental PV performance of these printable CPSCs under various light intensity conditions. To consolidate the proven stability of these CPSCs, we also present the results of one stability test standardized as ISOS-D-1,[64] which supports the potential for their deployment under mild indoor conditions. Moreover, we demonstrate a systematic comparison of the PV performance of these CPSCs under commonly available FL and LED-based lamps at various light intensities that replicate standard indoor environmental conditions. As a further advance, we also present the integration of these CPSCs for enhancing an electrical node as evidence of their potential to be used as an alternative light-harvesting solution for the targeted futuristic IoT-based ecosystem. Our results not only consolidate and contribute to the limited studies on this promising configuration of CPSCs, but also support the goal of achieving all printed and sustainable IoT devices with robust performance stability.

2. Results and Discussion

To begin our analysis, we first characterized the lab-sized (1.5 cm²) CPSCs to demonstrate their initial PV performance
with two selected aperture areas (0.14 cm², denoted as a small area, and 0.64 cm², denoted as a large area) under a standard xenon lamp-based solar simulator at various light illumination conditions. For the standard full sunlight condition, the fabricated batch of CPSCs in this work exhibited impressive (10.1 ± 1.5%) solar-to-electrical conversion efficiency over a small area (0.14 cm²), with the champion device reaching as high as 13.2 ± 2.2% conversion efficiency (Table 2, Figure 1a). This closely aligns with the PV performance for this device configuration indicated in various reports with similarly small aperture areas under standard full sunlight illumination conditions. Interestingly, the same batch of fabricated CPSCs revealed striking (11.1 ± 1.6% and 12.6 ± 1.8%) conversion efficiencies when measured under half and 0.1 sunlight illumination conditions, with the champion devices attaining an impressive 13% and >14% conversion efficiencies, respectively (Table 2, Figure 1a).

As a more realistic approach, we also measured the PV performance of the same batch of CPSC devices with a greater (0.64 cm²) active area, which is rarely reported for similar lab-sized devices of this configuration. 

Table 2. Average PV parameters (4 CPSCs) achieved at 1 Sun, 0.5 Sun, and 0.1 Sun light intensity conditions. The active area for small area measurements was 0.14 cm² and was 0.64 cm² for large area measurements. The values in brackets are of the champion device.

| Active area | Intensity | JSC [mA cm⁻²] | VOC [V] | FF [%] | η [%] | PMAX [mW cm⁻²] |
|------------|-----------|----------------|---------|--------|--------|----------------|
| Small      | 1 Sun     | 16.0 ± 1.7(17.7) | 0.87 ± 0.01(0.87) | 72 ± 3(77) | 10.1 ± 1.5(11.9) | 10.1 ± 1.5(11.9) |
|            | 0.5 Sun   | 8.8 ± 0.8(9.6)  | 0.86 ± 0.01(0.86) | 73 ± 4(78) | 11.1 ± 1.6(12.9) | 5.6 ± 0.8(6.5)   |
|            | 0.1 Sun   | 2.2 ± 0.2(2.3)  | 0.81 ± 0.02(0.82) | 72 ± 3(76) | 12.6 ± 1.8(14.4) | 1.3 ± 0.2(1.4)   |
| Large      | 1 Sun     | 15.7 ± 1.8(17.7) | 0.92 ± 0.01(0.93) | 64 ± 4(69) | 9.3 ± 1.6(11.4)  | 9.3 ± 1.6(11.4)  |
|            | 0.5 Sun   | 8.7 ± 0.9(9.7)  | 0.91 ± 0.01(0.92) | 68 ± 4(73) | 10.9 ± 1.8(13.1) | 5.4 ± 0.9(6.5)   |
|            | 0.1 Sun   | 2.1 ± 0.2(2.34) | 0.87 ± 0.01(0.88) | 71 ± 5(77) | 13.2 ± 2.2(15.9) | 1.3 ± 0.2(1.6)   |

Figure 1. Characterization results of the champion device a,b) J–V curves achieved at 1 Sun, 0.5 Sun, and 0.1 Sun light intensity conditions. a) The active area for small area measurements was 0.14 cm² (b) The active area for large area measurements was 0.64 cm² (c) Incident photon to collected electron efficiency (IPCE) response of the best CPSC. d) Results of maximum power point tracking test (MPPT) of the best CPSC under 1 Sun light intensity condition.
revealed comparable PV performance, i.e., without compromising the conversion efficiencies (average batch: 9.3 ± 1.6%; highest 11.4%) on a relatively larger active area under full sunlight illumination conditions (Table 2, Figure 1b). Systematically, we further extended our characterization with this larger active area to determine the PV performance of these CPSCs under half and 0.1 sunlight intensities, which again indicated higher conversion efficiencies (10.9 ± 1.8% and 13.2 ± 2.2%, respectively, Table 2).

Motivated by these initial characterizations, we further investigated the preliminary operational PV performance stability with a simulated maximum power point tracking test (MPPT) that was conducted under full sunlight illumination for more than two hours (as shown in Figure 1d). Contrary to traditional device structures, which often degrade rapidly under such stressful conditions, the fabricated CPSCs exhibited robust operational stability without showing any performance degradation for up to 150 min (i.e., >2 h, Figure 1d). These simulated conditions seem far more stressful with higher temperatures (38.5 ± 2.1 °C) combined with strong illumination compared to standard indoor conditions and provide a fair indication of reliable deployment of this printable device configuration of PSCs under more relaxed indoor building environmental-based ecological conditions.

To further support our perspective, we also simulated one of the standardized tests (ISOS-D-1) suggested for the indoor deployment conditions and provide a fair indication of reliable deployment of this big area based indoor ecological conditions. To this end, we extended our characterizations and further investigated their PV performance under versatile low light intensity conditions by selecting two types of commonly available light sources (FL and LED lamps) through their measured spectra as shown in Figure 3. We selected three light intensities (200, 500, and 1000 lux as shown in Figure 4), which correspond to 0.1–1% of the standard full sun irradiation conditions and typically generate a calculated output power >60–400 μW cm⁻² (Table 4) depending on the type of light source and the relative distance.

Moreover, to contribute to the traditional rationale regarding the PV performances for numerous architectures of PSC technology with small active areas, it is equally valuable to initially compare the performance of CPSCs with similarly small active areas.

Table 3. Average PV parameters (3 CPSCs) achieved at 1 sun light intensity condition during the initial measurements and after 1065 h of the room temperature (RT) aging test. The active area for small area measurements was 0.14 cm² and was 0.64 cm² for large area measurements.

| Active area | Scan | J_SC [mA cm⁻²] | V_OC [V] | FF [%] | η [%] | P_MAX [mW cm⁻²] |
|-------------|------|----------------|---------|--------|-------|-----------------|
| Small       | Initial | 13.1 ± 1.6 | 0.84 ± 0.01 | 69 ± 1 | 8.8 ± 1.1 | 8.8 ± 1.1 |
|             | After 1065 h | 17.3 ± 0.8 | 0.85 ± 0.01 | 71 ± 2 | 10.5 ± 0.7 | 10.5 ± 0.7 |
| Large       | Initial | 14.5 ± 1.7 | 0.90 ± 0.01 | 63 ± 1 | 8.3 ± 1.2 | 8.3 ± 1.2 |
|             | After 1065 h | 16.9 ± 1.0 | 0.91 ± 0.01 | 63 ± 2 | 9.7 ± 0.8 | 9.7 ± 0.8 |

Figure 2. a,b) J–V curves and PV parameters of the best CPSC achieved at 1 sun light condition during the initial measurements (blue) and after 1065 hours (red) of the RT aging test. a) The active area for small area measurements was 0.14 cm². b) The active area for large area measurements was 0.64 cm².
as reported with traditional device configurations of PSCs (Table 1). Hence, the small active area (0.14 cm²) based PV performance of the fabricated CPSCs was initially investigated under both the LED and FL light sources with the selective low light intensity conditions and is summarized in Table 5.

Output power as high as >72 μW cm⁻² under 1000 lux light intensity of a LED light source was achieved, corresponding to an impressive (≈21%) conversion efficiency observed for the best CPSC (Table 5 and Figure S3a, Supporting Information). The same CPSC exhibited >19% and >17% conversion efficiencies with corresponding ≈33 and >12 μW cm⁻² P_MAX values when measured under 500 and 200 lux light intensity sources, respectively (Table 5 and Figure S3a, Supporting Information). For the FL light source, the trends of PV performance also remained quite similar, where the same champion CPSC revealed comparable power output (Table 5 and Figure S3b, Supporting Information) with a range of >73, 34 and 13 μW cm⁻² when tested under similar light intensity values, respectively. Followed by these initial investigations, measuring the power output of CPSCs with a far larger active area provides the opportunity to more reliably assess their targeted integration into a variety of sustainable energy harvesting solutions. [3,79,80]

Table 6 summarizes the average PV performance of the same batch of CPSCs measured with a larger (0.64 cm²) active area, which revealed an impressive >80 μW cm⁻² power output (with striking conversion efficiencies, i.e., >20–23% utilizing both the light sources) for the champion CPSC when measured under 1000 lux (Figure 5a,b). Similarly, >38 and >14 μW cm⁻² values were achieved under 500 and 200 lux light intensities, respectively. These results not only confirm that there are no performance compromises despite the significant increase (>350%) in active area, but also establish better standards for comparing the performance of various traditional configurations of lab-sized PSCs often reported with marginal active areas, as listed in Table 1.

In addition, the dependence of the PV performance of CPSCs on light intensities (I) was further investigated, where V_OC and J_SC were obtained in response to varying light intensities used in this study (Figure 6).

In this regard, the linear dependence of V_OC on the logarithm of intensity (I) (Figure 6a,b) has remained as an established protocol in response to Equation (1), in which k is the Boltzmann constant, T is the temperature, the q is the elemental charge, n is the ideality factor, and C is denoted as a fitting parameter.[81–83]

\[
V_{OC} = \frac{n k T}{q} \ln(I) + C \tag{1}
\]

By using Equation (1), several recombination mechanisms can be predicted by calculating the ideality factor values, such as the...
bimolecular recombination process if it remains close to 1, whereas the monomolecular recombination mechanism dominates when it approaches 0.5. Based on the results of the measurements performed under the solar simulator (Figure 6a) and under indoor light sources (Figure 6b), we deduce the ideality factor values of the fabricated CPSCs as $\approx 0.9$ and $\approx 1.8$, respectively. This reveals the dominance of the bimolecular recombination process under strong light intensity conditions, whereas the monomolecular recombination (i.e., trap-assisted recombination) process persisted under low light intensities, in agreement with previous reports.\[67,86,87\]

Similarly, the behavior of $J_{SC}$ with varying light intensities ($I$) was also investigated using experimental data and linear fit with the power law as shown in Equation (2), where $\alpha$ is the fitting parameter.\[12,88-91\]

$$J_{SC} \propto I^\alpha$$  \hspace{1cm} (2)

Equation (2) similarly predicts recombination processes according to values achieved for $\alpha$. The second-order bimolecular recombination dominates if $\alpha$ approaches 0.5, whereas the first-order monomolecular recombination processes have been reported when the values remained close to 1.\[92,93\] With linear dependence of $J_{SC}$ over varying light intensities, the $\alpha$ values in our results remained $\approx 1$ under low-intensity lights (Figure 6d), indicating the dominance of the monomolecular (i.e., trap-assisted) recombination process. In contrast, the slope of $J_{SC}$ reduces to 0.87 (Figure 6c), indicating the evolution of bimolecular recombination as the light intensities increase. These results derive the same conclusions as observed from the linear dependence of $V_{OC}$ on the logarithm of intensity ($I$) measurement results, and also conclude the fading of charge trapping through defects in cases when the light intensity increases, as discussed in other reports.\[95-99\]

Interestingly, the findings also motivate the development of next-generation-based defect-free and highly efficient CPSCs where the monomolecular recombination or “trap-assisted recombination” (as a dominant recombination mechanism under low-light intensity conditions) could be potentially suppressed via numerous strategies, such as traps filling at the grain boundaries, electronic defects passivation through passivation molecules, or by performing intelligent interface engineering as reported for other types of device architectures for PSC technology.\[100-104\]

Furthermore, to reconsolidate the operational performance stability, we conducted another MPPT test for the fabricated CPSCs under these ambient ecological conditions for $>10$ h while using 1000 lux of one of the light sources (i.e., FL lamp). As expected, no sign of degradation was observed among any individual PV parameter, thus confirming the performance durability as also previously presented in a MPPT test under full sunlight illumination conditions (Figure 2d). Such ranges of output power combined with robust operational performance potentially validate the vast opportunities for this unique device design of PSC technology to realize its application in achieving novel, self-sustaining and advanced electronic ecosystems Figure 7.\[3,6,80\]
Finally, the capability of CPSCs is demonstrated by energizing a Light-based Internet of Things (LIoT) concept-based temperature sensing node (TSN) \([105]\) by harvesting ambient light (1000 lux) energy through them from the FL light source. The setup was made by constructing three individual units, which can be categorized as: 1) Energy Harvesting Unit, 2) TSN Electronics Control Unit (TSN-ECU), and 3) Data Control Unit (DCU), as shown in Figure 8.

In brief, the harvested energy from an array of CPSCs (in the energy harvesting unit) was first supplied to charge a prismatic supercapacitor (Capxx 0.4F 4.5 V)\([106]\). An Atmega 328p microcontroller \([107,108]\) (in the TSN-ECU) was selected as the TSN's controller component, which was programmed to function at a frequency of 8 MHz and voltage of 3.3 V to perform the operations between the TSN and optical wireless transceiver (OWT) \([105]\) with minimum power consumption. In addition, an ultra-low-power step-down DC–DC voltage converter \([109]\) was used to provide steady voltage (3.3 V) to the TSN-ECU (Figure 8). Moreover, the bidirectional optical communication links were established between the TSN-ECU and the DCU, which could be categorized as: a visible light communication link as a "downlink" (from DCU to TSN-ECU) and an infrared communication link as an "uplink" (from TSN-ECU to DCU)\([105]\).

Figure 9a represents the generated temperature data profile in response to the above-described experimental setup. The supercapacitor (Figure 9b) gets fully charged through CPSCs and maintained its operating voltage of \(\approx 4.5\) V during light harvesting intervals (i.e., illumination mode). It was supplied with a step-down voltage (3.3 V) to the TSN-ECU to enable the steady communication link between the TSN-ECU and the DCU.

The stored energy of the charged super capacitor was utilized (resulting in a voltage decay) to confront the uninterrupted
The operation of the TSN during the dark mode. The trends (Figure 9b) were progressively repeated during the testing period (6 days), thus confirming the stable and sufficient energy harvesting and delivering capability of the exposed CPSCs with the selected light intensity (i.e., 1000 lux) conditions.

With such proof of concept, novel and exciting user experiences, as well as applications, can be forecasted, where IoT-based solutions could provide sustainable and wirelessly connected sensor networks to promote among others, smart working environments and safer livings in homes and buildings. In this regard, ambient indoor light harvesting has been envisioned to play a key role in achieving low cost, fully printed, and energy-efficient solutions for massive data exchange and communication inside modern-built environments. Also, an effective influence on reducing greenhouse emissions could be possible, which has often been indicated in the case of deploying PVs in natural outdoor climatic conditions.\[110–112\]

Interestingly, the lifetime of supercapacitors at RT-based operating conditions, in general, remains far higher than traditional rechargeable batteries\[113–116\] and offers opportunities for realizing infinite functioning lifetime-based maintenance-free IoT solutions as demonstrated in this work.

Figure 8. Schematic diagram of light-based Internet of Things (LIoT) concept-based bi-directional communication capable temperature sensing node that was operated by harvesting ambient light (1000 lux) energy with a fluorescent (FL) light source.

Figure 9. a) Generated temperature data profile from the temperature sensing node (TSN) used in this work b) Charging-discharging profile of the supercapacitor used to energize the TSN and electronics control unit (ECU).
From such key viewpoints, the printable CPSC devices fabricated in this work hold immense potential for meeting numerous above-mentioned characteristics and developing self-power-based autonomous solutions for indoor applications. With an extended FTO–glass substrate, advanced intelligent electronic circuits to perform versatile operations could be designed and printed adjacent to the CPSC stack, as illustrated in Figure 10. This could allow wireless connectivity between the CPSCs and the intelligent printed circuits through depositing high-performance printable conductors such as copper ink-based innovative strategies offered to facilitate printed electronic-based solutions in recent years.[117,118] As a result, low cost, fully printed, and durable light-harvesting solutions could be envisioned to meet the rapidly increasing demands of IoT-based solutions.

3. Conclusions

To conclude, we successfully demonstrated various capabilities of a low-cost and printable configuration of PSC technology through fundamental PV performance characterizations to consolidate their possible deployment in indoor environments. The fabricated lab-sized CPSCs revealed high performance with impressive conversion efficiencies, which reached between 11% and 15% when tested under standardized conditions with various light intensities and the significantly larger active area selected for this study. Moreover, the devices exhibited robust stability when exposed to one of the tests (ISOS-D-1) recommended for next-generation-based PV technologies and did not show any performance deviation for a period of 1065 h. Followed by these findings, we also investigated their PV performance under various low light intensity conditions with FL and LED light sources. Output powers as high as 81.5, 38.4, and 14.5 μW cm⁻² with impressive conversion efficiencies were achieved over significantly larger (0.64 cm²) active areas under 1000, 500, and 200 lux light intensities, respectively. These output powers are likely sufficient to energize a wide range of low-powered electronic devices located inside buildings,[3,79] and provide a far more reliable state-of-the-art compared to the PV performance of other configurations of PSC technology, often reported with very small active areas for lab-sized devices under similar low-intensity light conditions.

As a further advance, we also demonstrated the successful functioning of an IoT-based TSN via harvesting ambient light energy through these CPSCs to record the continuous temperature data of selected indoor ecological conditions. The results presented in this work provide opportunities to further develop fully printed and maintenance-free energy harvesting-based solutions to meet the growing demand for self-powered IoT-based electronic ecosystems presently needed for various applications inside modern building environments.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

C.M.T.K.: Experiments planning, CPSC sealing and characterizations, stability testing, IoT node fabrication planning, data analysis, and writing the original manuscript draft. M.A.N.P.: IoT node fabrication and related experiment planning, data analysis, and writing. M.K.: Data analysis related to IoT, commenting, and reviewing the manuscript. D.M.: CPSC fabrication, data analysis, writing, reviewing, and commenting on the manuscript. S.G.H.: supervised the research work and contributed with funding acquisition, experimental planning, data analysis, writing, review, and editing of the overall manuscript.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

indoor, low light, perovskite solar cells, stability
[117] J. Wiklund, A. Karakoç, T. Palko, H. Yiğitler, K. Ruttik, R. Jäntti, J. Paltakari, J. Manuf. Mater. Process. 2021, 5, 89.

[118] Y. Bonnassieux, C. J. Brabec, Y. Cao, T. B. Carmichael, M. L. Chabinyc, K.-T. Cheng, G. Cho, A. Chung, C. L. Cobb, A. Distler, H.-J. Egelhaaf, G. Grau, X. Guo, G. Haghiashian, T.-C. Huang, M. M. Hussain, B. Iniguez, T.-M. Lee, L. Li, Y. Ma, D. Ma, M. C. McAlpine, T. N. Ng, R. Österbacka, S. N. Patel, J. Peng, H. Peng, J. Rivnay, L. Shao, D. Steingart, R. A. Street, V. Subramanian, L. Torsi, Y. Wu, Flexible Printed Electron. 2021, 6, 23001.