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Mini Review

DSSCs for Indoor Environments: From Lab Scale Experiments to Real Life Applications

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Abstract:

A mini review is presented on recent advances in the area of DSSCs for indoor operation, focusing on both lab scale experiments and industrial applications. The suitability of DSSCs for indoor operation, when compared to other PV technologies, is highlighted and the perspective for universal DSSCs, that are able to maintain their performance during radical changes in their lighting environment, is presented.

***Keywords:** Dye sensitized solar cell (DSSC); indoor lighting; Building integrated/applied photovoltaics (BIPV/BAPV); Product integrated photovoltaics (PIPV) ; electrolyte optimization;*

Introduction

There has been a recent re-emergence of Dye Sensitized Solar Cells (DSSCs [1]) and a key factor for this is their suitability for operation under indoor lighting environments. This is especially evident in their potential applications in buildings and devices. Building applied and building integrated photovoltaics (BAPV/BIPV) [2] as well as product integrated photovoltaics (PIPV) [3]-especially for low power electronics- are some of the more promising applications for DSSC. BAPV are photovoltaics applied on existing building infrastructure, while with BIPV, common building materials can be replaced with power generating elements [3], both allowing for energy generation in close proximity to where energy is required, streamlining the operation. Meanwhile, PIPV permit power generation from PV embedded on the product itself. These applications require novel technologies that perform well, when operating under low intensity light environments (most often indoors or under diffuse light). DSSCs can be easily manufactured using low-cost wet-chemistry processes, they have an eco-friendly profile, their efficiency is independent from the light's angle of incidence and they present a variety in color and transparency [4]–[6]. However, what makes them especially attractive for the aforementioned applications is their excellent performance under low intensity light.

Indoor lighting conditions are strikingly different from solar irradiated environments both in light intensity and in emission spectra [7]. The disparity in light intensities is enormous: An illuminance of ~400 lux is expected in an office room (lux being the measurement unit for indoor light intensity), while the standard 1 sun AM1.5G irradiation (Standard Test Conditions, STC, $100 mW/cm^2$) corresponds to $\sim10^5$ lux [7], [8]. Thus, performance under 1 sun cannot be indicative of indoor performance.

For example, poly-Si (polycrystalline silicon), a cornerstone PV technology with good performance under solar irradiation, severely underperforms when placed under indoor light [7]. Instead, it is thought that amorphous thin films and nanomaterials are more suitable for diffuse incident light [9]. In fact, it is has been confirmed that the efficiency of DSSCs increases, when the light intensity decreases under 20 mW/cm^2 [7], [10]. This characteristic puts DSSCs in an advantageous position when working under weak solar light conditions (e.g. under cloud covered sky) and justifies their superiority versus OPVs and silicon cells [11], [12] under indoor lighting.

Indoor focused DSSC optimization research

The basic principle of DSSC operation [13] is the excitation of dye molecules (chemisorbed in the form of a monolayer onto a semiconductor, designated as working electrode) followed by the injection of the electrons into the semiconductor conduction band. The photogenerated charges are then collected by the electrode substrate, while the dye is regenerated by a redox mediator in the electrolyte present between the photoanode and the counter electrode. A lot of efforts have been devoted to the development of efficient components (electrodes, dyes, electrolytes, redox couples) and there has been increased interest in the research community towards optimizing DSSCs for indoor conditions.

Freitag et al. (2017) [14], prepared a copper redox-DSSC co-sensitized with the highly performing XY1/D35 dyes that achieved 28.9% efficiency under 1000 lux of fluorescent light, outperforming GaAs cells. Power generation of this magnitude was considered sufficient for the autonomous operation of a range of electronic devices operating indoors. In another of their works, for the powering of autonomous Internet of Things (IoT) devices -with machine learning capability- under ambient light, Michaels et al (2020) [15] prepared copper electrolyte based DSSCs through co-sensitization (XY1/L1), reaching 34% efficiency under 1000 lux of fluorescent light.

In the work of Yiming Cao et al (2018) [16] DSSC configurations, with the Y123/XY1b dye combination and copper electrolytes, were prepared and characterized under 1 sun and under indoor fluorescent light. The''1 sun'' version of their DSSCs had the required redox species (Cu(II)) concentration for sufficient mass transport, while the ''indoor performing'' version of their cells was prepared with significantly lowered redox species concentration, in order to reduce recombination. A 2.8 cm^2 cell achieved 31.8% efficiency under 1000lux fluorescent light (outperforming reported silicon, GaAs, OPV and perovskite cells).

As for advances concerning the simpler robust [I^-/I_3^- redox - Ru dye] DSSC configuration, Rossi et al. (2015) [4] customized a N719-DSSC with a low I_2 content I^-/I_3^- electrolyte, thereby preparing an indoor optimized DSSC with an efficiency of 12.4% under 200lux fluorescent light, the highest reported efficiency for I^-/I_3^- DSSCs under fluorescent light. Their customized device outperformed other tested PV technologies such as a-Si and p-Si. As expected, though their optimization strategy allowed for a highly performing indoor DSSC, the same modifications led to a decrease in performance under 1 sun (STC).

Industrial applications

As mentioned before BIPV/BAPV/PIPV benefit greatly from DSSC technology under indoor environments. An ever-increasing number of companies have turned their sights on the potential for indoor operating DSSCs [17]–[19], such as H.Glass [20], a Switzerland based manufacturer of glass-sealed DSSC solar panels for glass facades and building materials, with applications in indoor and outdoor environments or Fujikura, with DSSC modules customized for performance under specific light intensity conditions [5].

For Sweeden-based Exeger [21], one of the areas of interest is the powering of electronic devices with natural and artificial light by solar cell integration, turning devices such as wearable electronics, tablets and e-readers into self-powered devices. In the area of BIPV, their goal is for one square meter of façade to power one square meter of office space. Their solar cells are purported to take advantage of even diffuse and indoor light in order to produce electricity ''from dawn until dusk''.

GCELL [17]'s lightweight DSSCs, designed for indoor energy harvesting product applications, are attuned to the 50-2000 lux lighting intensity range. Their cells are reported to generate a power density of 4-7 $\mu W/cm^2$ at 200 lux, allowing for indoor powered sensors, e-readers and other applications.

In 2016, GCell introduced the world's first indoor solar powered iBeacon, which uses renewable energy to enable broadcasting. Furthermore, their solar cells have been used as part of a hotel's large scale indoor solar system [22] for the powering of motorized blinds.

3GSolar [11], another provider of DSSC for electronic devices, has set a goal of replacing finite power sources in electronic devices with integrated miniature PV cells that harness energy from indoor or outdoor environment and achieve wireless and maintenance-free operation for the lifetime of the device (more than ten years). In low light conditions (under 2700k LED, 1000 lux), 3GSolar cells can reach ~16% efficiency. One such product is their Bluetooth sensor [23], able to operate under light intensities of over 100 lux.

Future perspectives: the importance of DSSC adaptability to different lighting conditions

From the above cases, the superiority of DSSCs when compared to other PV technologies under indoor light sources, is especially evident. What is also evident, however, is the ''fork'' in optimization strategies when considering outdoor or indoor DSSC operation conditions. Optimizing a PV device for indoor environments usually detracts from its 1 sun performance [7], which is why specific operation environment designations are seen, even in industrial products [19]. Many past studies and industrial products present DSSCs singularly optimized for either high or low intensity operation conditions, because of the trade-off between indoor/outdoor performance optimization. The adaptability of DSSC can be further enhanced and it is crucial for them to be able to maintain their performance when the nature the incident light changes, regarding intensity or emission spectrum.

The disparity between lab testing conditions and real life operation conditions is known for energy systems [24]–[26]. Under realistic operation conditions, the performance of a PV device [27] is not expected to remain identical to the performance evaluated under ideal lab conditions due to changes in light intensity and other factors concerning the surrounding environment [7] (e.g. daily cycle). Especially for handheld PIPV devices such as tablets, for which the operation environment is expected to change often (e.g., from outdoors to indoors), a DSSC optimized singularly for a specific lighting environment will not sufficiently cover energy needs (due to decreased performance during operation under lighting conditions different from the initially targeted ones). Thus, the perspective of a single DSSC maintaining performance even when the lighting conditions radically change must be adopted during the optimization step. And, as the electrolyte is one of the key parameters that defines the final DSSC's optimization goal, focus should be placed on its proper formulation for maximum DSSC operational flexibility.

The most common DSSC configuration utilizes a (dye-sensitized) mesoporous TiO_2 thin film as the semiconductor and a redox electrolyte (based on copper, cobalt or I^-/I_3^- shuttles, with differences in molecule size, charge, redox potential, etc that strongly affect the device performance) as the medium. There are factors (such as transparency) that depend on the concentration of redox species in the electrolyte, with the most significant being the mass transport of the redox species and the prominence of recombination during operation.

Device function under high solar light intensities usually requires high concentrations of redox species [7], [28] for sufficient dye regeneration, while, for operation under indoor light sources, lower concentrations are needed to prevent negative effects such as the recombination of electrons [29]. Thus, a finely tuned formulation must be achieved in DSSCs, in order to enhance indoor operation without impairing the function under higher intensity light. The universal ''pan-illumination'' function of DSSCs, good performance under a wide range of different lighting conditions, is a requirement for modern BIPV/BAPV and PIPV applications.

Conclusions

In this brief survey, lab and industrial scale advances on the application of DSSCs in indoor environments were summarized and the need for single universally applicable DSSCs (offering good ''pan-illumination'' performance, under radically different lighting conditions) was highlighted. When compared with other PV technologies, DSSCs have proven especially suitable for utilization in low light intensity environments with very high efficiencies achieved and many DSSC-integrated products already on the market. Further enhancement of their usage flexibility and adaptability in changing light conditions is bound to consolidate their place as prime candidates for BIPV, BAPV and PIPV applications regardless of the lighting environment under which they operate.

Author Contributions

Conceptualization, investigation, writing-original draft preparation, visualization: George V. Belessiotis; writing-review and editing: Islam Ibrahim; supervision, writing and review: Chaido S. Karagianni, Polycarpos Falaras. All authors have read and agreed to the published version of the manuscript.

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References

1. B. O'Regan and M. Grätzel, "A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO2 films," *Nature*, vol. 353, no. 6346, pp. 737–740, 1991.
2. Grand View Research, "Dye Sensitized Solar Cell Market Analysis By Application (Portable Charging , BIPV / BAPV , Embedded Electronics , Outdoor Advertising , Automotive (AIPV)) And Segment Forecasts To 2022," 2016.
3. C. J. Traverse, R. Pandey, M. C. Barr, and R. R. Lunt, "Emergence of highly transparent photovoltaics for distributed applications," *Nat. Energy*, vol. 2, no. 11, pp. 849–860, 2017.
4. J. Goldstein, I. Yakupov, and B. Breen, "Development of large area photovoltaic dye cells at 3GSolar," *Sol. Energy Mater. Sol. Cells*, vol. 94, no. 4, pp. 638–641, 2010.
5. Fujikura, "https://www.fujikura.co.uk/products/energy-and-environment/dye-sensitized-solar-cell."
6. F. Sauvage, S. Chhor, A. Marchioro, J. E. Moser, and M. Graetzel, "Butyronitrile-based electrolyte for dye-sensitized solar cells," *J. Am. Chem. Soc.*, vol. 133, no. 33, pp. 13103–13109, 2011.
7. F. De Rossi, T. Pontecorvo, and T. M. Brown, "Characterization of photovoltaic devices for indoor light harvesting and customization of flexible dye solar cells to deliver superior efficiency under artificial lighting," *Appl. Energy*, vol. 156, pp. 413–422, 2015.
8. E. E. Richman, "Requirements for Lighting Levels." [Online]. Available: http://www.lumitronlighting.com/lighting_nowledge/LUX LEVEL_usace_Requirements for Lighting Levels.pdf.
9. A. Sacco, L. Rolle, L. Scaltrito, E. Tresso, and C. F. Pirri, "Characterization of photovoltaic modules for low-power indoor application," *Appl. Energy*, vol. 102, pp. 1295–1302, 2013.
10. N. Tanabe, "Dye-Sensitized Solar Cell for Energy Harvesting Applications," Fujikura Tech. Rev., vol. 42, pp. 109–113, 2013.
11. Technology presentation. Https://www.3gsolar.com/technology, "3GSolar."
12. N. Sridhar and D. Freeman, "A study of Dye Sensitized Solar Cells under Indoor and Low Level Outdoor Lighting: Comparison to Organic and Inorganic Thin Film Solar Cells and Methods to Address Maximum Power Point Tracking," *Conf. Proc. 26th EU-PVSEC*, pp. 232–236, 2011.
13. A. Hagfeldt, G. Boschloo, L. Sun, L. Kloo, and H. Pettersson, "Dye-sensitized solar cells," Chem. Rev., vol. 110, no. 11, pp. 6595–6663, 2010.
14. M. Freitag et al., "Dye-sensitized solar cells for efficient power generation under ambient lighting," Nat. Photonics, vol. 11, no. 6, pp. 372–378, 2017.
15. H. Michaels et al., "Dye-sensitized solar cells under ambient light powering machine learning: Towards autonomous smart sensors for the internet of things," Chem. Sci., vol. 11, no. 11, pp. 2895–2906, 2020.
16. Y. Cao, Y. Liu, S. M. Zakeeruddin, A. Hagfeldt, and M. Grätzel, "Direct Contact of Selective Charge Extraction Layers Enables High-Efficiency Molecular Photovoltaics," Joule, vol. 2, no. 6, pp. 1108–1117, 2018.
17. Solar cell description. Section: "Electrical performance". Https://gcell.com/gcell-products/custom-solar-cell, "GCell."

18. Ricoh, “https://www.ricoh.com/technology/tech/066_dssc.”
19. “3GSolar product page.”
20. “H.Glass.” [Online]. Available: http://h.glass.
21. “Exeger.” [Online]. Available: https://exeger.com/applications
22. “Skyco Shading Systems with G24 cells.”
23. “Energy harvesting demonstration kit,” E-peas semiconductors and 3Gsolar, 2018.
24. C. Cornaro, L. Renzi, M. Pierro, A. Di Carlo, and A. Guglielmotti, “Thermal and electrical characterization of a semi-transparent dye-sensitized photovoltaic module under real operating conditions,” Energies, vol. 11, no. 1, 2018.
25. G. V. Belessiotis, K. G. Papadokostaki, E. P. Favvas, E. K. Efthimiadou, and S. Karellas, “Preparation and investigation of distinct and shape stable paraffin/SiO2 composite PCM nanospheres,” Energy Convers. Manag., vol. 168, pp. 382–394, 2018.
26. N. Stathopoulos, G. Belessiotis, P. Oikonomou, and E. Papanicolaou, “Experimental investigation of thermal degradation of phase change materials for medium-temperature thermal energy storage and tightness during cycling inside metal spheres,” J. Energy Storage, vol. 31, 2020.
27. M. Pierro, F. Bucci, and C. Cornaro, “Full characterization of photovoltaic modules in real operating conditions: Theoretical model, measurement method and results,” Prog. Photovoltaics Res. Appl., vol. 23, no. 4, pp. 443–461, 2015.
28. M. I. Asghar, K. Miettunen, S. Mastroianni, J. Halme, H. Vahlman, and P. Lund, “In situ image processing method to investigate performance and stability of dye solar cells,” Sol. Energy, vol. 86, no. 1, pp. 331–338, 2012.
29. H. Ohno, “Electrochemical Aspects of Ionic Liquids,” 2nd ed., John Wiley & Sons, Inc., 2011, pp. 150–151.

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