

Article

A New Type of Architecture of Dye-Sensitized Solar Cells as an Alternative Pathway to Outdoor Photovoltaics

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Abstract: The current investigation shows a possible new pathway for more efficient and cost-effective energy-harvesting photovoltaic devices. Our approach could permit all emerging technologies that are currently used for indoors and smart buildings to go a step forward and could be used for outdoor applications. The investigated architecture is a very promising geometry especially for Dye-Sensitized Solar Cells (DSSCs). It turns their main drawback, the lowering of their efficiency and lifetime when operating at high solar irradiation density, into an asset by increasing the total active area per horizontal unit area for light harvesting, while preserving the active elements from degradation and extending durable lifetime. The investigated architecture is based on a symmetric “U” type geometry, which is constructed by a highly reflective material on the inner surface. Solar irradiation is reflected internally at the bottom of the construction and splits towards two opposite sided solar cells; the two cells form a cavity where the solar light multiplies and is successively absorbed. Consequently, the vertically incoming irradiation is reduced when reaching the vertical internal sides on which the DSSCs are mounted. Thus, the solar cells operate at low light intensities, which provide significant lifetime extension and efficiency enhancement. Interestingly, the electrical energy per effective surface unit, which is produced by the two vertical DSSCs, is at least equal to that of a standalone, vertically irradiated cell. The advantage of the new architecture is that protects DSSCs from their degradation and deterioration, although the entire system operates under high illumination. This makes the cells more efficient outdoors, with a comparable performance to indoor conditions.

Keywords: solar; photovoltaics; dye-sensitized solar cells; DSSCs; solar trap; vertical geometry; outdoor applications



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1. Introduction

In the global race to reduce greenhouse gas emissions, several renewable energy technologies have been under intense investigation. These include hydropower [1], tide-wave-ocean [2], geothermal [3], wind [4], solar photovoltaic [5], solar thermal devices [6], ambient heat (heat pumps) [7], biofuels [8] and renewable municipal waste [9]. Solar technologies constitute a sizable chunk given the abundance of solar energy (~1 h of solar irradiation amounts for annual global energy needs [10,11]). Solar photovoltaics (PV), which directly convert light into electricity, are well-suited for a variety of indoor and/or outdoor applications and at different application scales, e.g., small-scale roof-top and window installations or large-scale solar park facilities.

According to the primary light-absorbing material, photovoltaic technologies are classified into wafer-based and thin-film technologies. The former consists of (i) crystalline silicon (c-Si), (ii) gallium arsenide (GaAs) and (iii) III-V multijunction (MJ) solar cells.

Thin film technologies are divided into commercial thin-film PVs and emerging thin-film technologies [12]. Multijunction cells are the most efficient nowadays with power conversion efficiencies up to 47.1% [13], followed by single-junction GaAs cells, which can achieve up to 30.5% [14], c-Si cells that can reach 27.6% [15] and thin film technologies which perform in the range of 14 to 23.35% [16]. Emerging PV are within 12 to 29.1% [17] with monolithic perovskite tandem cells exhibiting the leading performance among them [18].

Despite their lower efficiency, emerging PV technologies, such as thin films, perovskites (PPV), organic PVs (OPV) and dye sensitized solar cells (DSSC) have emerged in recent years as attractive and promising alternatives due to their low cost, simple preparation methods, low toxicity, abundance of raw materials and easy production. They are generally more stable and efficient under low light intensities due to their internal thermal processes that can be damaging above one sun illumination, in contrast to c-Si solar cells [19–22]. Efficient power generation under weak irradiation is essential for indoor applications, enabling Internet of Things (IoT) devices and “smart” buildings and installations in cloudy places. More specifically, the power conversion efficiencies of DSSCs and perovskite solar cells increase dramatically at low light intensities [19]. Cost-effective and environmentally friendly graphene dotted Pt-free DSSC [23], ruthenium-based DSSCs with graphene quantum dots [24], efficiently and stable quasi-solid-state dye-sensitized solar cells (QS-DSSCs) based on N719 dye [25] or high-efficiency bifacial DSSCs [26] have been considered as promising solutions for DSSCs applications at room light conditions. As a matter of fact, DSSCs play a great role as indoor power sources [27] and are widely used in wearable electronics and flexible energy production [28–33]. OPV technology has climbed up to 26% [34,35], while perovskite technology has increased up to 30% [36] under low light conditions.

To increase the efficiency of PV cells, various techniques have been investigated, such as tandem solar cells [37–42] where the light with a shorter wavelength is absorbed by the outermost material with a wide band gap, while the light with a longer wavelength is transmitted through and absorbed by the material with the narrower band gap. Many efforts have been made to improve the performance of tandem thin films for geometric light trapping [43,44], including combinations with materials in tandem technology [45–48]. Theoretical characterizations of organic solar cells from the literature have been realized by various methods [49]. Furthermore, a materials-independent method for cell-efficiency improvement is light trapping with parabolic concentrators [50,51].

In this research work we investigate an alternative geometry that enables the outdoor usage of DSSCs while retaining their advantages under low light conditions; the proposed geometry is generic and may be applied to any emerging PV with an optimized performance at low light intensities. In particular, the proposed architecture splits internally the incoming solar light and distributes it towards two individual vertical cells. This approach increases the effective active area without changing the overall cell cross section and reduces the illumination density. We report on a fill factor enhancement of the included cells of nearly 90% to 96% under direct sun illumination and an efficiency enhancement for each cell as well.

Dye Sensitized Solar Cells

The first DSSC PV cell was introduced by Brian O’ Regan and Michael Grätzel in 1991 [52]. It is basically an electro-chemical cell with a mesoporous and spongy dye-coated semiconductor. A DSSC consists mainly of five different parts: (i) a conductive thin film on a soda lime glass substrate as a photoanode, (ii) a nanocrystalline semiconductor thin film, (iii) a dye as a light-harvesting element, (iv) an electrolyte for liquid state devices or a hole transport material for a solid state DSSC and (v) a platinum or carbon coated conductive glass as a counter electrode. The two electrodes are sealed with a sealing gasket.

The operational process of DSSCs starts with the photon absorption by a dye sensitizer. Excited electrons from the HOMO to the LUMO state of the dye are transferred to the conduction band of the semiconductor creating a charge separation between the dye

and TiO_2 . Oxidized dye is regenerated by electrons from the HOMO state of the redox electrolyte, which in turn is regenerated by the initially produced electrons that have travelled through the external circuit from the photoanode to the platinum hole transport layer on the counter electrode. The LUMO of the dye must be higher than the conduction band of TiO_2 , while the HOMO of the dye should be lower than the redox potential of the electrolyte or the hole transport material for better dye regeneration.

DSSCs can be fabricated on a variety of substrates such as glass, flexible or polymer materials. Blade coating, spin coating, spray coating, electro-hydro-dynamic spray deposition, dip coating, brush painting, screen printing and sputtering are various fabricating methods of the semiconductors for emerging PV technologies. The semiconductor thin film [53] is photosensitized by dyes such as N719 [54], N749 (black dye) [55], N3 [56], CYC-B11 [57] and C106 [58] that have been considered as the most suitable materials for DSSCs, while there are many other types of organic and metal free dyes. Electrolytes could be liquid or solid charge transport materials [59], while in relation to the hole transport layer of the counter electrode, platinum [60] is the most suitable coating for achieving high power conversion efficiencies due to its outstanding electrocatalytic properties.

2. Experimental Section

2.1. Materials and Fabrication Methods

Medium scale ($1.9 \text{ cm} \times 1.4 \text{ cm}$ in size) nanostructured TiO_2 films were deposited on soda-lime glass substrates with FTO (fluorine doped tin oxide) as a conductive layer (Greatcell solar TEC 7 glass plates, 3 mm thickness with a sheet resistance of $7 \Omega/\text{sq}$ and 75–80% transmittance in visible light). FTO glasses were cleaned with a soft detergent followed by ultrasound treatment first in acetone (about 10 min), then rinsed with ethanol and immediately immersed in ethanol for a 10 min ultrasound. The FTO glasses rinsed with DI water were then heat treated [61] on a hot plate for 10 min at 125°C for drying, then at 450°C for 30 min. The TiO_2 paste was ground in a mortar for at least 30 min by adding it into 7 gr TiO_2 nano-powder (Aeroxide TiO_2 P25, 20–25 nm particle size) in HNO_3 [62–64] aqueous solution 1.5M in 1 mL increments while it was ground for the mechanical separation of the aggregated TiO_2 particles until a uniform paste was achieved. The uniform paste was put in an ultrasonic bath for 5 min to breakdown any agglomerates of TiO_2 nanoparticles that were not broken up. Finally, three drops of a non-ionic surfactant Triton-X were added as a modifier of the paste to facilitate the spreading of the paste, reducing the surface tension and the formation of cracks. Photoanode electrodes were pre-treated in a TiCl_4 aqueous solution (Acros Organics, Titanium (IV) chloride, 99.9%, MW 189.71 g/mol). For the TiCl_4 treatment, the working electrodes were immersed in a 40 mM aqueous TiCl_4 solution at 70°C for 30 min, rinsed with DI water after cooling, cleaned with acetone on the opposite side of the FTO glass to take away any remaining particles, then dried for 5 min on a hot plate at 50°C [65–67]. The TiO_2 paste was deposited on the working electrode by screen printing that results in more uniform coatings [68–70]. A screen mask of $1.4 \text{ cm} \times 1.9 \text{ cm}$ was developed on a mesh T-100 (Saatilene hi-tex) polyester screen printing fabric with a mesh count of 100 T mesh/cm, a mesh opening of $55 \mu\text{m}$, a nominal thread diameter of $40 \mu\text{m}$, a 31% open area, a fabric thickness of $63 \mu\text{m}$, a theoretical past volume of $20 \text{ cm}^3/\text{m}^2$ and a specific cross section of $0.126 \text{ mm}^2/\text{cm}$. The distance between the pre-treated FTO glass and the mesh T-100 was adjusted to 3 mm. The paste was deposited in a single step on the working electrode by a spatula. A second layer of paste was deposited after 5 min since the first layer had to be calm and dry. The final electrodes were annealed at 500°C for 45 min by increasing the temperature stepwise (5 min at 125°C , 5 min at 250°C , 5 min at 350°C , 15 min at 450°C , 15 min at 500°C). The “double layer” TiO_2 film was treated again by immersion in a 40 mM TiCl_4 solution (post treated photoanode) as described in the pre-treatment procedure and then sintered at 500°C for 45 min as in the previous step. The nanocrystalline TiO_2 photo electrodes were warmed at 80°C and they were immediately immersed in a 0.5 mM N719 dye ethanol solution (Greatcell Solar CAS No 207347-46-4, powder) at room temperature for 24 h to ensure complete sensitizer uptake.

Upon extraction from the solution, the samples were thoroughly rinsed with methanol to remove excess dye. Counter electrodes with a size of $2.5\text{ cm} \times 2.5\text{ cm}$ were drilled with a 3 mm diameter drill and heat treated as the photoanode electrode. Two drops of Greatcell Solar Counter Electrode Solution—Isopropanol, Dihydrogen hexachloroplatinic (IV) hydrate with a charge transfer resistance (R_{ct}) $6.08\ \Omega \times \text{cm}^2$ were spread on the FTO surface and then annealed at $400\text{ }^\circ\text{C}$ for 15 min. For the assembly of the electrodes, a low temperature thermoplastic sealant (Greatcell Solar) with a melting point at $93\text{ }^\circ\text{C}$ and a thickness of $50\text{ }\mu\text{m}$ was used. The sealant was cut into $2.0\text{ cm} \times 2.5\text{ cm}$ pieces with an inner hole of $1.4\text{ cm} \times 1.9\text{ cm}$ that was placed between two electrodes on a hot plate at $110\text{ }^\circ\text{C}$ for sealing. A high-performance solution of acetonitrile, 1-Butyl-3-methylimidazolium iodide, valeronitrile, 4-tert-butylpyridine and lithium iodide, iodide (Greatcell Solar EL-HPE) was used as the electrolyte. The electrolyte was filled into the cell through the counter electrode holes using a pipette. The holes were sealed at the back of the counter electrode with small pieces of low thermoplastic sealant and a microscope glass ($2.0\text{ cm} \times 2.5\text{ cm}$) using a hot iron bar.

2.2. Electrical Characterization

An adjustable solar simulator power supply (Sciencetech Inc. 550-200-PS, London, ON, Canada) was used for the electrical characterization of the fabricated DSSCs with an internal xenon lamp (Osram xbo 150 w/cr, Berlin, Germany) for irradiance densities of up to $100\text{ mW}/\text{cm}^2$ (the equivalent of one sun at air mass AM1.5). The incident photon energy power was measured by a DeltaOhm HD2302.0 light meter with an LP471 RAD probe with a resolution of $0.1\text{ mW}/\text{m}^2$ in the spectral range of 400–1050 nm. A source measurement unit (Keithley 2601 SMU, Cleveland, OH, USA) was used for conducting measurements in the 2-wire mode. Keithleys' extracted data were processed by a program in Labview where the appropriate parameters were calculated.

2.3. Experimental Procedure

DSSCs were implemented in ambient conditions. The aim was to find an easy way to implement cells on a larger active surface area as usual (medium scale DSSCs). A total of 170 DSSCs were developed and successfully characterized with various TiO_2 coating techniques (doctor blade, spin coating, screen printing) to achieve the construction of medium-sized cells, with the best performance, reproducibility, and stability. The efficiencies of the cells that were fabricated with the doctor blade and spin coating methods were up to 2.6% and 3.1%, respectively. The screen printing method proved to be the best in relation to their stability, efficiency (up to 3.06%) and active surface uniformity, regardless of their size. The TiO_2 paste coating was deposited in one, two or three steps successively to fine tune the screen-printing procedure. The method with the double-layered film was more efficient.

A total of 53 screen printed cells were fabricated in two different processes of the thin nanocrystalline TiO_2 layer for photoanode preparation. In the first one, titanium isopropoxide-TTIP ($\text{C}_{12}\text{H}_{28}\text{O}_4\text{Ti}$) was used (24-cells) for TiO_2 post-treatment, while in the second method titanium (IV) chloride (TiCl_4) was used as a post-treatment process (29-cells). The photoanodes of all cells were pre-treated with TiCl_4 solution.

The TTIP method results did not have the proper stability with low efficiencies and had problems in both the TiO_2 post-treatment and TiO_2 dye adhesion. On the contrary, the TiCl_4 method was more stable. The XRD analysis of the final nanocrystalline TiO_2 layer showed that it was mainly constituted from TiO_2 anatase with a few rutile and brookite (Bruker Advance8 system). Optical profilometry aimed to find an appropriate average thickness of the TiO_2 layer of about $20\text{ }\mu\text{m}$ (Polytec TMS—1200 TopMap). Transmittance of the fabricated photoanodes, cells and dye absorber were also taken by FRMonitor-ThetaMetrisis (Peristeri, Greece). Irradiation cycles of the fabricated final cells were made to improve their stability at different power intensities over time.

For our research purposes, a fine reflective surface had to be implemented. Important parameters for the selection of this material were the capability of producing different shapes by an easily scalable process, as well as the total cost per surface unit. We ended up selecting Silver Plated Brass (SPB) instead of pure silver as a low cost and more obtainable solution in the case of larger DSSC arrays. The purpose of this surface was to reflect the remaining solar irradiation that passes through a semitransparent DSSC, not only back to the cell itself for producing additional free charge carriers but also towards the opposing cell in order to exploit the entire energy of the light beam via multiple reflections. At the same time, the SPB surface acts as a UV absorber that protects certain elements of the DSSCs.

Figure 1a depicts a medium scale ($1.9\text{ cm} \times 1.4\text{ cm}$) DSSC cross section.

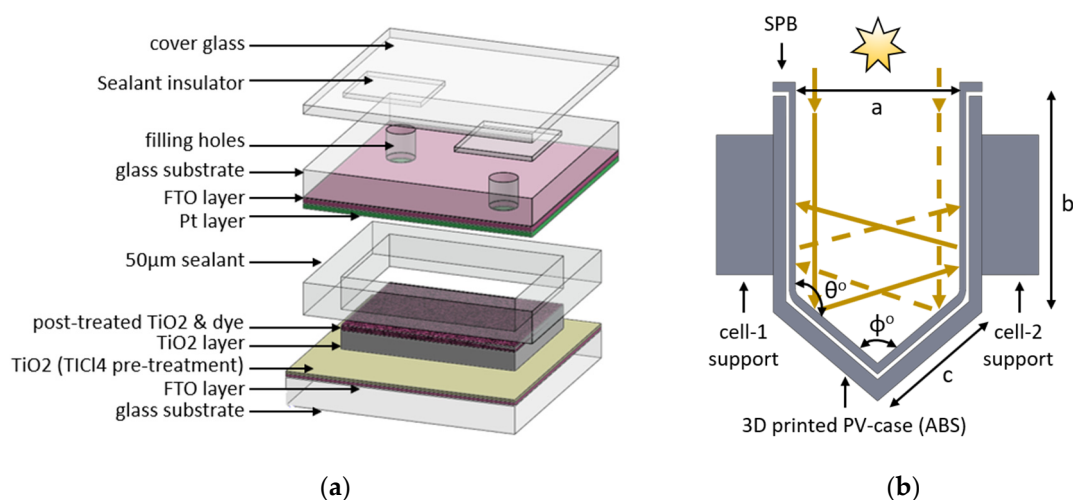


Figure 1. (a) Cross section of a dye sensitized solar cell, (b) Light path into the proposed PV case; the golden arrows depict schematically the light path of the vertically incoming solar beam, its splitting and the multiple reflections.

The cell consisted of a 3 mm glass substrate with an FTO layer as a conductive surface, a thin nanocrystalline TiO₂ layer that was pre/post treated by the TiCl₄ aqueous solution, a dye for energy absorption, a 50 μm sealant as a spacer between the electrodes into which its inner gap the electrolyte I^-/I_3^- had to be injected and a thin Pt layer as a hole transport layer on the FTO-treated back contact electrode. Finally, two pieces of the same sealant were used for cell sealing with a microscope glass (1 mm thickness) as a cover glass. The method by which the liquid electrolyte was injected into the inner gap of the cell as well as the Pt deposition on the counter electrode by drop casting was one of the reasons why the the poor quality of the constructed cells was reinforced.

Figure 1b depicts a cross section of the geometry as an alternative light trap for the improvement of DSSCs such as dye sensitized solar cells. This kind of cell case (DSSC-case/PV case) was designed and sketched by a CAD program and built by a 3D printer with ABS material as well. SPB was stretched into the same design geometry and was integrated inside the PV case. Two prominences were designed to the left and to the right of the PV case to support the DSSCs. Photoanodes were exposed to radiation through two internal windows with the same surface area, while appropriate pieces of SPB were placed at the back of the DSSC cells as a light surface reflection. The light path of the radiation into the PV case is also shown in Figure 1b. As the distance (a) between the cells was 1.4 cm (upper area 2.52 cm^2) and the vertical length (b) was at 2 cm equal to the cells' height and they were kept constant, the internal angles θ° and ϕ° as well as the (c) length (Figure 1b) were calculated for the maximum light path before the photons escaped from the PV case. The main objective was the absorption of the energy from each cell gradually every time photons impinged on them.

The PV case was designed with a floor plan surface equal to the active area of each cell for a better and easier comparison of the results. Accordingly, the incident photon energies were equal in the three cases of the electrical characterization.

The electrical characterization of the DSSCs was performed under 1.5 AM at different intensities of irradiation in all steps. At first, the DSSCs were characterized as alone cells under 1 sun illumination (standalone cell—Figure 2a). As a second step, a piece of SPB (2 cm × 2.5 cm) was placed at the back of each cell mounted with binder clips and the same measurements were taken (SPB cell, Figure 2b). Finally, both cells were placed vertically into the support “ears” of the PV case with SPB pieces at the back of the counter electrodes (double cell architecture, Figure 2c). SPB pieces had the same dimensions (2 cm × 2.5 cm) as above with a larger surface than the active area of the cells, thus minimizing any irradiation leaks due to the scattering of light through the glass substrate.

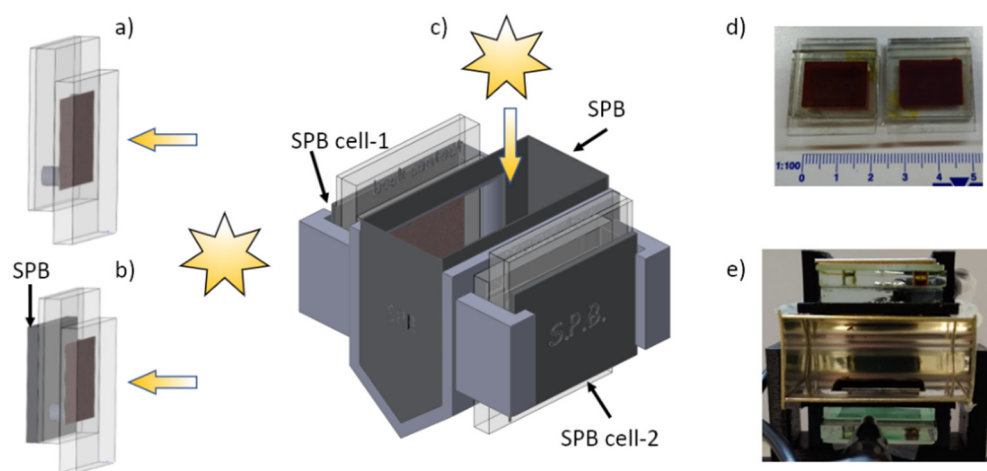


Figure 2. (a) Standalone cell, (b) SPB cell, (c) PV case: double cell architecture, (d) DSSCs; actual size, (e) experimental architecture (PV case) with mounted DSSCs.

At first, cells alone and SPB cells were characterized under 500, 750 and 1000 W/m² power densities to investigate the effect of silver-plated brass on the characteristic parameters of the cells. In addition, the cells were measured under 200, 500 and 1000 W/m² power densities as standalone cells (without SPB at the back of them), as well as into the current PV case under the same variable illumination (Figure 2a,c). Moreover, silver-plated brasses were placed to the left and to the right of the double cell architecture to reduce irradiation losses and to promote multiple reflections between the two sides of the PV case, thus producing more charge carriers in the cells.

3. Results and Discussion

SPB reflectivity was measured by an FR Monitor device (ThetaMetrisis SA) in the range of 200–900 nm. (Figure 3a). It came out that at low wavelengths SPB absorbed more radiation, while for wavelengths above 350 nm the absorption was less and the reflection increased, thus rendering the SPB suitable for the cells' absorption. This was an SPB advantage since UVA exposure plays a critical role and DSSC cells degrade quickly under UV illumination. The authors think that the cells' performance degradation occurred because of the TiO₂-photocatalyzed attack on the electrolyte which led to the consumption of the triiodide in the electrolyte, while wavelengths below 390 nm cause direct band gap excitation of the TiO₂ semiconductor [71,72]. Moreover, N719 that was used as a dye absorbed photons in the range of 350 to 600 nm as shown in Figure 3b, suggesting that silver-plated brass is an appropriate material for the reflected irradiance.

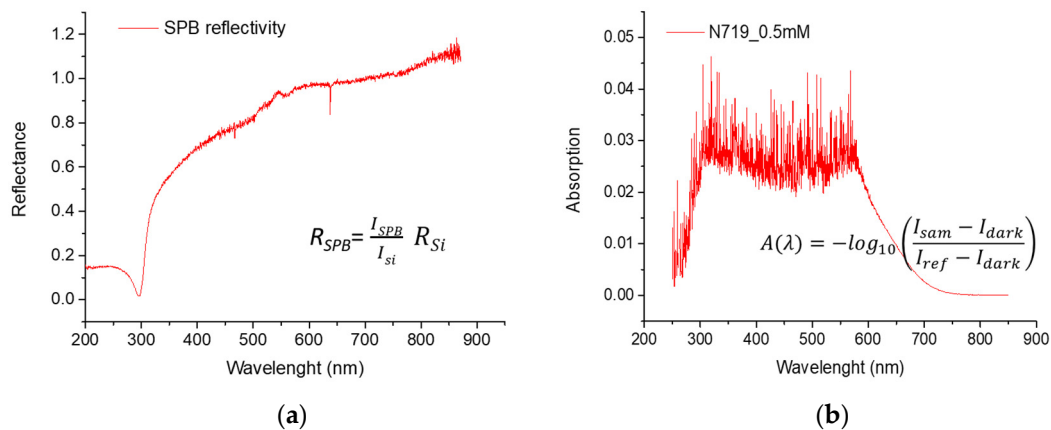


Figure 3. (a) Silver-Plated Brass Relative Reflectivity, (b) N719 optical absorption.

A total of 46 DSSC devices were fabricated using the screen-printing method by different photoanode treatments with N719 dye as a sensitizer while 7 DSSCs were with fabricated with N749 dye (Table 1). They were measured as standalone cells at an incident power of 1000 W/m². Their power conversion efficiency (PCE) and fill factor (FF) were measured to be up to 3.06% and 0.33 for the N719 sensitized cells, while cells with N749 dye were measured up to 2.23% and 0.36, respectively. Although the devices were sensitized with either N719 or N749 dyes they had the same electrical response, while their results were similar.

Table 1. DSSC screen-printed fabricated devices.

Dye	Number of Cells	Active Area (cm ²)	Pin (watt/m ²)	Best Performance		
				FF	PCE (%)	Jsc (Max) (mA/cm ²)
N719	46	2.52	1000	0.33	3.06	9.9
N749	7	2.52	1000	0.36	2.23	13.4

In this work we present the electrical measurements of two DSSCs with N719 in the role of the absorber. Figure 4 depicts the enhancement of the characteristics of a successfully fabricated cell with N719 as the dye sensitizer. An improvement of 0.4% to 0.48% to PCE and 0.02 to 0.05 to FF (20% to 25% and 9% to 14% increase, respectively) at variable irradiation densities was observed when SPB was added at the back side of the cell (Table 2).

Table 2. Results of the effect of SPB on the cells' performance.

DSSC	P _{in} (watt)	Active Area (cm ²)	PCE (%)	FF	Isc (mA)	Voc (V)	Jsc (mA/cm ²)
Cell (N719)	500	2.52	2.51	0.38	12.98	0.64	5.15
	750	2.52	1.92	0.32	17.23	0.65	6.84
	1000	2.52	1.60	0.29	20.44	0.66	8.11
SPB cell (N719)	500	2.52	2.99	0.44	13.41	0.64	5.32
	750	2.52	2.37	0.37	18.55	0.66	7.36
	1000	2.52	2.00	0.32	23.21	0.67	9.21

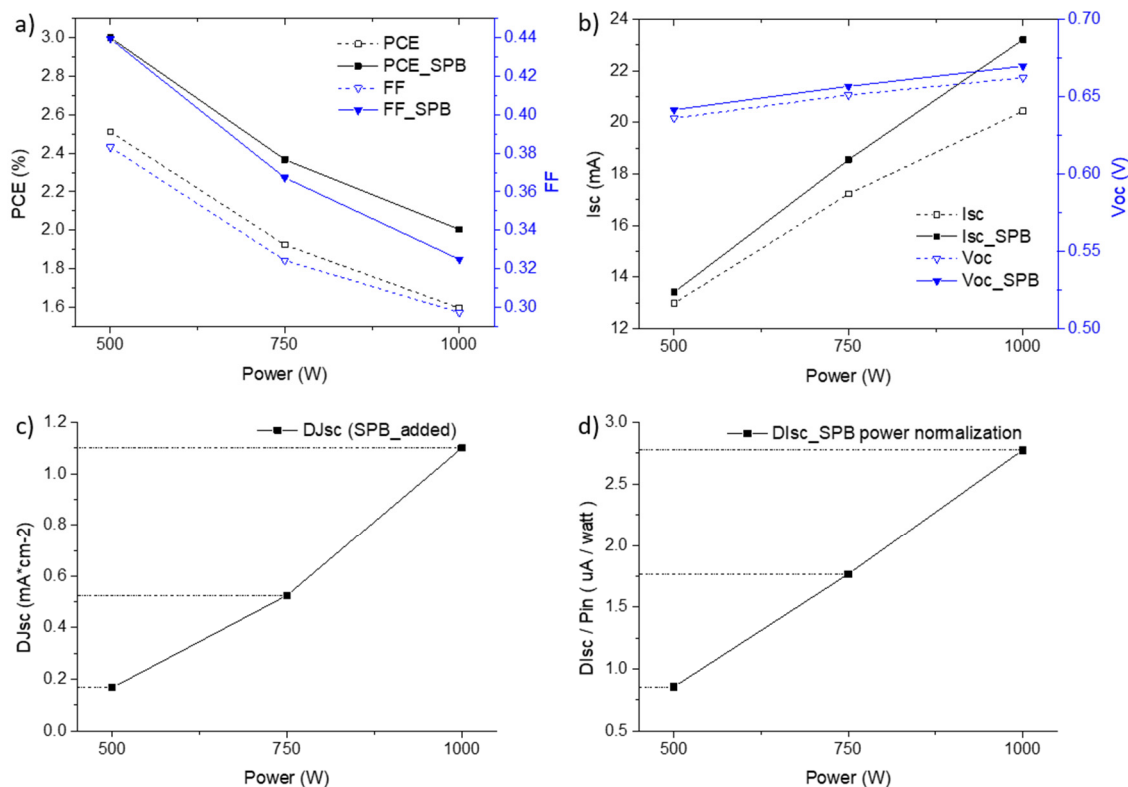


Figure 4. Electrical characterization results for alone cells vs. SPB cells. SPB effect on (a) PCE/FF, (b) Isc/Voc, (c) DJsc after SPB addition, (d) DIsc normalized with power.

SPB addition caused an improvement of 3% to 13% (500 to 1000 W/m²) in current density (Figure 4c) while an increase of 0.8 to 2.7 μA per watt (Figure 4d) was observed. This demonstrates that part of the incident light that was not absorbed in the first pass through the cell was reflected back to the cell from the SPB mirror leading an extra generation of charge carriers and thus photocurrent.

The greatest improvement, however, was observed when these devices were illuminated at a lower power. Figure 4a,b depict the effect of the illumination power (500, 750 and 1000 W/m²) in devices with and without SPB, demonstrating in both cases the severe performance drop upon increasing the input power. Specifically, PCE dropped by 36% between 500 and 1000 W/m², FF dropped by 22%, while V_{oc} marginally increased by 4%.

The stability of the devices and measurements was verified by performing thirteen consecutive measurement cycles within the power density range 200–1000 W/m², with full reproducibility of results observed. The errors estimated from these measurements were less than the point sizes in the curves; in particular, the errors were of the order of 10^{-3} for all parameters. These results directly point to DCSSs being suitable for utilization in indoor applications only. Due to the mechanical stress of the DCSSs during the electrical characterization in different ways as standalone cells, or SPB cells and also into the PV case, it was not possible for each cell to complete a whole measurement cycle. Therefore, other fabricated cells, with the same recipe, were characterized for the rest of our research. At the final step of our research, cells were characterized as standalone cells under one sun variable illumination and then placed into the investigated architecture (PV case) to be measured under the same variable power densities too.

Figure 5 provides the comparison of the I-V curve performance at 1000 W/m² illumination, in between cell1 and cell2 as standalone cells (without SPB behind them) and the same cells as cell1/PV case and cell2/PV case after their placement into the new architecture (PV case). The corresponding parallel shunt resistance R_{sh} , which is shown with the slope of the I/V near the short circuit current point, was calculated according to the literature [73–75]

and it was significantly lowered in the case of standalone cells compared to the case of the new architecture (cell1/PV case, cell2/PV case) where a higher shunt resistance (lower $1/R_{sh}$ factor) was observed.

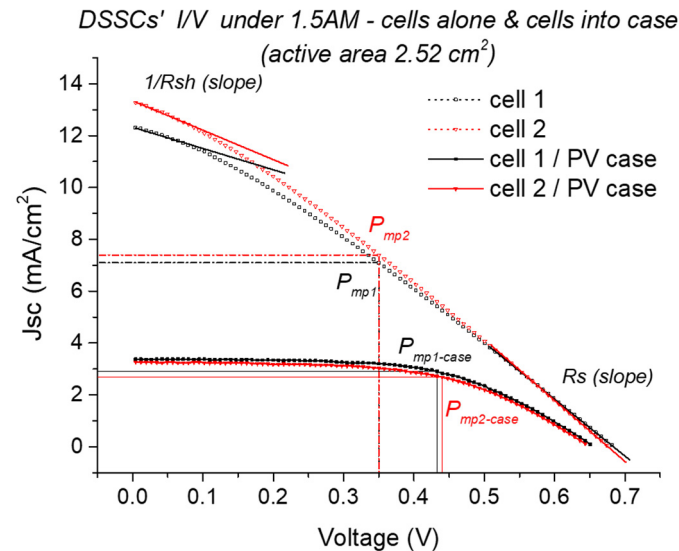


Figure 5. DSSCs' raw data under 1.5 AM—cell1, cell2: I/Vs of alone cells, cell1/PV case, cell2/PV case I/Vs when the cells are placed into the PV case.

Equations (1) and (2) show the way the shunt and series resistance affected the fill factor (FF) of the DSSCs and gave a new value to it (FF'). It came out that the higher shunt resistance is, the lower the influence on the fill factor of the cells, while the higher series resistance is, the greater the effect of the fill factor is. This improvement of R_{sh} meant that less electron-hole recombination took place in the photoanode layer with a reduction in charge carriers' loss. The increased value of R_{sh} resulted in an improved fill factor (1), while the series resistance (R_s) was not affected.

$$FF' = FF \left(1 - \frac{1}{R_{sh}}\right) \quad (1)$$

$$FF' = FF(1 - R_s) \quad (2)$$

$$FF = \frac{J_{mp} \times V_{mp}}{J_{sc} \times V_{oc}} \quad (3)$$

$$PCE = \frac{P_{mp}}{P_{in}} \times 100\% = \frac{J_{sc} \times V_{oc} \times FF}{P_{in}} \times 100\% \quad (4)$$

The increase in the fill factor (3) caused higher efficiencies (4) only in the case where J_{sc} and V_{oc} remained unchanged. However, in our case (Figure 5) when the cells were placed into the PV case, V_{oc} was nearly the same, while the current density (J_{sc}) was reduced noticeably due to the lowering of the power density inside the PV case. J_{sc} was reduced from 12.3 and 13.3 mA/cm² for cell1 and cell2, to 3.4 and 3.3 mA/cm², respectively i.e., a reduction of about 72% and 75%, respectively. The power density at the internal windows of the PV case was measured with the pyranometer and it was found to be nearly 240 W/m². This improvement in the fill factor caused an enhancement in the PCE due to the power density reduction.

The results of the electrical characterization under variable power densities (200, 500, 1000 W/m²) of the cells as standalone and in the PV case are also presented in Figure 6. The values of the corresponding parameters are shown in Table 3.

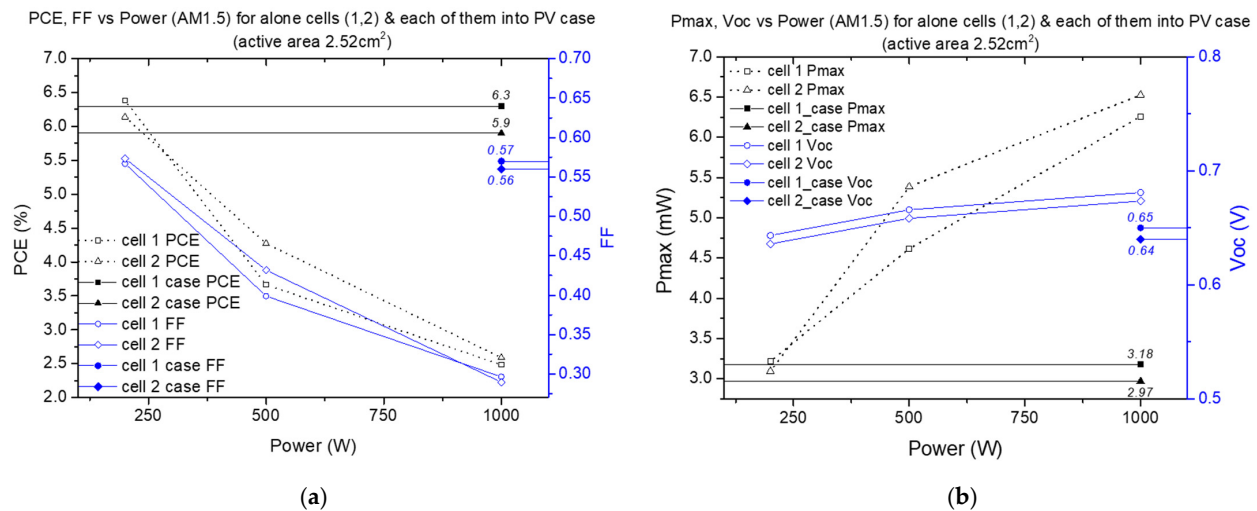


Figure 6. Characterization results of alone-cells and in the PV case also. The PV cases' impact on the cells' parameters. (a) efficiency and fill factor, (b) Pmax and Voc of each occasion.

Table 3. Electrical characterization results for alone-cells/cells in the PV case.

DSSC	P_{in} (watt)	Active Area (cm ²)	V_{oc} (V)	J_{sc} (mA/cm ²)	PCE (%)	FF	P_{max} (mW)
cell 1	200	2.52	0.64	3.50	6.38	0.57	3.22
	500	2.52	0.67	6.90	3.67	0.40	4.62
	1000	2.52	0.68	12.31	2.48	0.30	6.26
cell 2	200	2.52	0.64	3.37	6.14	0.57	3.09
	500	2.52	0.66	7.52	4.27	0.43	5.39
	1000	2.52	0.67	13.27	2.59	0.29	6.53
cell 1 PV case	1000	2.52	0.65	3.38	6.30	0.57	3.18
cell 2 PV case	1000	2.52	0.64	3.27	5.90	0.56	2.97

In the measurements of stand-alone cells (cell_1_PCE, cell_2_PCE) the efficiency was improved from 2.48% and 2.59% under 1000 W/m² to 6.38% and 6.14% under 200 W/m², while the corresponding fill factor (cell_1_FF, cell_2_FF) was improved from 0.30 and 0.29 to 0.57 for both cells, respectively (similar to indoor applications). After their placement into the PV case, with the power density of the irradiation of the hole device at 1000 W/m² and at the internal windows of PV case at 240 W/m², the final efficiency of each cell (cell-1-case-PCE, cell-2-case-PCE) reached the values of 6.30% and 5.9%, while the fill factor (cell-1-case-FF, cell-2-case-FF) attained the values of 0.56 and 0.57, respectively (Figure 6a and Table 3). Although the whole geometry was under 1000 W/m², the efficiencies of both cells that were placed inside were increased due to the redundancy of the power irradiation at nearly the same values that were measured in the case of 200 W/m² as standalone cells. The efficiency of each cell was enhanced by nearly 137% to 157% under one sun direct illumination, respectively.

Figure 6b presents the open circuit voltage (V_{oc}) and maximum power (P_{max}) fluctuation of each cell before and after their placement into the PV case. V_{oc} did not change significantly in and out of the PV case. The difference in the V_{oc} values was about 30 mV for each of them. The cells' maximum power (cell_1_Pmax, cell_2_Pmax) was reduced under variable power densities of 1000–200 W/m² from 6.26 mW and 6.53 mW to 3.22 mW and 3.09 mW, respectively (similar to indoor applications). After their placement into the PV case with the density of the power devices below 1000 W/m², they behaved as if they were standalone at about 200 W/m² with the values of the maximum power point (P_{max}) of 3.18 mW and 2.97 mW, respectively. As mentioned above, the power density at the internal windows of the PV case was found to be about 240 W/m². Consequently, the behavior of

the in the PV case was the same as they were directly under a cloudy sun with a power of density of 200 W/m^2 despite the fact that the whole device was illuminated with one sun irradiation.

It is noteworthy that while both cells were placed into the PV case, the maximum power produced by them reached the value of 6.15 mW ($3.18 \text{ mW} + 2.97 \text{ mW}$), which was nearly the same as the maximum power of each cell alone under a 1000 W/m^2 power density (6.26 mW for cell1 or 6.53 mW for cell2).

In addition, calculating the total efficiency of the devices with the two sub-cells placed into Equation (4) with a total power generation of $(3.18 + 2.97) \text{ mW} = 6.15 \text{ mW}$, an active area of 2.52 cm^2 and an incident power of 1000 W/m^2 , we ended up with an efficiency of 2.44% which was nearly the same as in the occasion of a standalone DSSC under one sun. The impact of the SPB was limited only to the implementation of a solar trap that reflected the incoming solar radiation density on the active areas of the cells resulting in solar density degradation as well.

One might wonder about the reason why the investigated architecture is useful, since the total energy production per unit area was equal to the case of a standalone DSSC under one sun illumination. What is the benefit of the PV cases? For this question, the answer is simple. The effect of the new architecture was the improvement in the fill factor at high values ensuring the stability of the solar cells, while the whole device remained under one Sun illumination. Therefore, instead of using a simple dye sensitized solar cell outdoors, it is possible, via this architecture (with an equal horizontal surface area under one sun), to produce equal energy, thus extending their lifespan and protecting them from their degradation under high density illumination. This means that the current investigated architecture protects DSSCs when they are exposed to high solar densities outdoors and could be an important step for more green energy on the rooftops of buildings. Another important issue is that current investigated architecture in the future will follow any improvements in DSSC technology that degrades at high solar densities.

Additionally, masks with different apertures could also be placed on the top of standalone cells and the PV case to investigate more efficient alternative solutions with the specific architecture.

4. Conclusions

In this study, an alternative vertical PV architecture that can achieve low-light illumination conditions in outdoor applications, and the full implementation of solar energy was proposed. This architecture is of particular relevance to DSSCs', which operate better under low light illumination. Therefore, trivial DSSCs were used as a demonstration and proof of concept. The used DSSCs were electrically characterized as standalone cells under one sun illumination, as well as components in the vertical architecture (DSSC-case/PV case). The design of this architecture was adjusted for optimum light reflection toward the active areas of the cells, while scalable Silver-Plated Brass (SPB) back-reflectors were placed behind the cells in order to exploit the entire incident solar energy as well as UV-protection absorbers.

The present architecture converts the horizontal surface exposed to solar irradiation into vertical surfaces in which the incident irradiation intensity onto the vertical cells is substantially reduced, resulting in the cells' outdoor performance to achieve an increased indoor efficiency. This architecture converts DSSC's disadvantages, including their low efficiency, into an advantage for their outdoor usage. Their efficiency more than doubles, and the fill factors' enhancement is substantial. This results in more efficient DSSCs with an extended lifespan and protection for outdoor applications, protecting them from the sun's high irradiation and preventing their degradation and deterioration. It is very important that the total electrical power that is produced using this architecture is almost equal to the corresponding power energy generated by a standalone cell that simultaneously benefits from the aforementioned advantages.

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