



# Characterization of photovoltaic devices for indoor light harvesting and customization of flexible dye solar cells to deliver superior efficiency under artificial lighting



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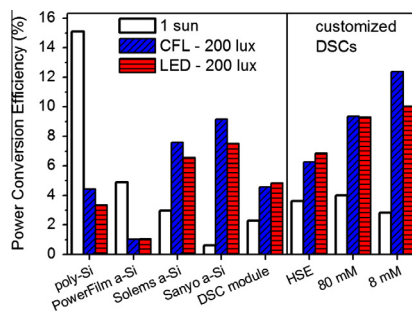
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## HIGHLIGHTS

- Experimental setup for photovoltaic measurements under indoor and low-level artificial light.
- Characterization of PV devices under commonly used illuminants (i.e. LED and CFL).
- Customization of flexible dye solar cells to deliver superior efficiency for light harvesting.
- Customized dye sensitized solar cells outperformed amorphous silicon devices at 200 lux.

## GRAPHICAL ABSTRACT



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## ABSTRACT

The field of energy harvesting holds the promise of making our buildings “smart” if effective energy sources can be developed for use in ambient indoor conditions. Photovoltaics (PV), especially in its thin flexible form for easy integration, become a prime candidate for the aim, if tailored for low-density artificial light.

We designed a test system which enabled us to measure the performance of PV devices under compact fluorescent lamp (CFL) and light-emitting diode (LED) illumination at different illuminance levels and compared polycrystalline and amorphous silicon cells with our own flexible dye solar cells (DSCs). Whereas poly-Si cells, with 15% outdoor efficiency, delivered at 200 lux under CFL only  $2.8 \mu\text{W}/\text{cm}^2$  power density (and an efficiency of 4.4%), a-Si specifically designed for indoors, gave  $5.9 \mu\text{W}/\text{cm}^2$  and 9.2% efficiency under the same CFL conditions (and 7.5% efficiency under LED).

However, we show that the customization of flexible DSCs, by simply formulating ad-hoc less-concentrated, more transparent electrolytes, enabled these devices to outperform all others, providing average power densities of  $8.0 \mu\text{W}/\text{cm}^2$  and 12.4% efficiencies under 200 lux CFL (more than quadruple compared to those measured at 1 sun), and  $6.6 \mu\text{W}/\text{cm}^2$  and 10% efficiency under 200 lux LED illumination.

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## 1. Introduction

The development of a light harvesting technology that delivers remarkable output power in indoor and low-level light conditions

has tremendous potential for application in the field of domotics and building management systems [1–5]. It would enable the generation of a class of self-powered, easy-to-install devices, such as intelligent sensors that communicate wirelessly, cutting down maintenance costs and ensuring flexibility to building management systems without the need for changing pre-existing infrastructures, and thus helping the rapid growth of the potentially huge technology field of the “Internet of Things” [6].

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Solar cells are a prime candidate for harvesting available light inside buildings, even if they have been initially developed for and typically measured at Standard Test Conditions (STC), i.e. 1000 W/m<sup>2</sup> normal irradiation, with AM1.5G spectral coefficient and a temperature of 25 °C [7–11], which are fundamental in enabling comparison between panels and reliability and uniformity of testing worldwide but far from those usually experienced in indoor environments, both in the spectrum (which is mainly concentrated in the visible region whereas the sun has a strong component in the IR) and radiant light intensity (typically up to ~3 orders of magnitude smaller compared to those specified at STC).

During the last decade, a number of papers have monitored the performance of different photovoltaic technologies, such as crystalline silicon, amorphous silicon, DSCs, polymer PV and CIGS under full outdoor conditions [12–19]. Performance depends on the modules response to spectral, reflection, temperature, irradiance, and nominal power variations occurring throughout the day and the seasons [14]. It is thus important also to consider not only the total energy produced outdoors by different panels over the course of a time period [20,21] but also how the performance varies and responds to different parameters in varying operating conditions, including indoors.

Whereas crystalline silicon dominates the market for outdoor installations, with its spectral sensitivity designed to match natural sunlight, amorphous silicon (a-Si) and dye sensitized photovoltaic cells are the strongest candidates for indoor applications [5,22–25].

The technology of dye solar cells (DSCs) has attracted strong industrial interest [26,27] and even products have been launched. Flexible dye solar cells (DSCs) [25], in particular, being light weight and easy-to-tailor in shape and dimensions, represent not only a possible way to harvest more of the sunlight's energy over the device's footprint by increasing its capture area when used curved [21], but also an efficient and appealing technology for energy harvesting even from artificial light in buildings, delivering noteworthy power densities to feed a wide variety of sensors and devices [28]. Although the remarkable indoor performance of DSCs has been announced, especially by companies, such as Texas Instruments [24], Fujikura [29], G24 Power [30] and Ricoh [31], surprisingly – and presumably because of industrial secrecy and the lack of indoor measurement protocols – no studies on the customization of DSCs for indoor use are present in the literature.

Here, we first set up an indoor photovoltaic testing station which can be equipped with different artificial illumination sources and which allows photovoltaic measurement at different illuminance levels. We selected compact fluorescent lamps (CFLs) and light-emitting diodes (LEDs), being currently the most-used illuminants. Subsequently, we present a systematic study of different technologies for light harvesting, both rigid and flexible, monitoring their performance at different levels of illumination under both CFLs and LEDs, noting a very large variation when compared to measurements taken under a solar simulator at STC. The PV devices studied were poly-crystalline silicon (poly-Si), as the benchmark for outdoor PV, different forms (both flexible and rigid) of commercial a-Si, up till now the major technology used for integration in indoor applications (e.g. those found in light-powered calculators) and DSCs fabricated in our laboratories, in their thin flexible form that enables a potentially more seamless integration in electronic sensors and devices [25]. We show that whereas the efficiency of poly-Si drops very significantly when measured indoors, that of a number of a-Si and all DSCs (even those designed for STC) increases considerably. Finally, we customized flexible DSCs with a thin metal foil working electrode and a transparent plastic counterelectrode, formulating different electrolytes, not for STC, but to deliver impressive power densities under artificial

indoor lighting, demonstrating how their performance can be made to surpass that of even the best a-Si device we tested.

## 2. Materials and methods

### 2.1. PV cells and modules

Four types of solar cells based on different photovoltaic technologies, i.e. polycrystalline and amorphous silicon, were provided by the suppliers and/or manufacturers listed in Table 1 and compared in this study. The fifth type was a flexible parallel DSC module with the photoanode on titanium foil and an electrodeposited platinum counterelectrode, fabricated at our CHOSE labs according to a previously reported procedure that enables one to electrodeposit the Pt catalyst over large areas via conducting fingers, which then function also as the current collecting grid in completed modules [32]. The commercial electrolyte and dye used were HSE (Dyesol) and N719 (Dyesol) respectively.

### 2.2. Fabrication of small area DSCs and electrolyte formulation

Indium-doped tin oxide – coated polyethylene terephthalate, ITO/PET (Flexvue, 15 Ω/sq) was cut with a CO<sub>2</sub> laser in 2.5 × 2.5 cm<sup>2</sup> samples, which were ultrasonically cleaned in isopropyl alcohol for 10 min. Then the samples underwent platinum electrodeposition (with pulsed current method: 5 mA/cm<sup>2</sup>, 5 cycles,  $t_{on} = 1$  s,  $t_{off} = 4$  s) from an aqueous solution of 10 mM hexachloroplatinic acid, 10 mM potassium chloride and 10w% Triton X. A G300 potentiostat/galvanostat (Gamry Instruments Inc.) as the current source was used and a purpose-built three electrodes system, consisting of the ITO-PET sample as the working electrode, a Ti foil as the counterelectrode and an Ag/AgCl electrode as the reference electrode. After the electrodeposition, the platinized ITO-PET samples were rinsed with deionized water and dried at 100 °C for 15 min.

Electrolytes based on the iodide/triiodide ( $I^-/I_3^-$ ) redox couple in 3-methoxy-propionitrile (MPN) were prepared, changing the iodine concentration, i.e. 80, 40, 20 and 8 mM, while keeping constant the remaining components: 0.7 M tetrabutylammonium iodide (TBAI), as the iodide source, 0.15 M guanidinium thiocyanate, 0.15 M N-methylbenzimidazole. Please note that, as iodine associates readily with  $I^-$  to form  $I_3^-$ , the concentration of triiodide equals that of iodine, while the concentration of  $I^-$  is that of TBAI lowered by the concentration of iodine = triiodide, i.e. large excess. All the solvents and chemical reagents were purchased from Sigma Aldrich.

Titanium foil (125 μm, Goodfellow) was used as the photoanode substrate and polished both mechanically and chemically via H<sub>2</sub>O<sub>2</sub> immersion at 95 °C for 40 min, followed by a thermal annealing at 450 °C for 30 min. It was then immersed in a 40 mM aqueous solution of TiCl<sub>4</sub> solution at 70 °C for 30 min and rinsed in de-ionized water and in ethanol. An opaque TiO<sub>2</sub> paste (NR-AO Dyesol) was screenprinted on the Ti substrate and sintered at 525 °C for 30 min. TiCl<sub>4</sub> treatment was repeated and followed by a thermal process at 500 °C for 30 min. The final TiO<sub>2</sub> thickness was ~15 μm.

Photoanodes were sensitized by soaking into a 0.3 mM ruthenium-based N719 dye solution in ethanol overnight, washed with the same solvent and dried before cell assembly. Each photoelectrode was sealed together with a counterelectrode and the cell (0.5 × 0.5 cm<sup>2</sup> active area) was completed by injecting the  $I^-/I_3^-$ -based electrolytes with different iodine concentration. A commercial electrolyte, HSE from Dyesol, was also used for comparison.

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