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Lifetime of organic photovoltaics: Linking outdoor and indoor tests

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ABSTRACT

A comprehensive outdoor study of polymer solar cells and modules for duration of one year was conducted. Different sample geometries and encapsulations were employed in order to study the spread in the lifetimes. The study is a complimentary report to previous work that focused on indoor ageing tests. Comparison of the indoor and outdoor lifetimes was performed by means of the o-diagram, which constitutes the initial steps towards establishing a method for predicting the lifetime of an organic photovoltaic device under real operational conditions based on a selection of accelerated indoor tests. Acceleration factors were determined using the ISOS-protocols, which enabled reproducible data acquisition between different laboratories and operators within the OPV community. A semi-automatic filtering method was employed for processing data acquired in outdoor tests. It was found that the lifetime of the samples tested under outdoor conditions was somewhere between the lifetimes of samples measured in accelerated indoor test conditions of damp heat and light soaking (ISOS-D-3 and ISOS-L-2) and in moderate indoor test conditions (shelf life and high temperature storage). The presented results reveal that while the accelerated ageing studies reveal days and weeks of lifetime for the studied samples, in outdoor real operational conditions the samples demonstrate stability up to months and seasons.

1. Introduction

Organic photovoltaic (OPV) is an emerging solar cell technology that has presented consistent growth in efficiency over time [1]. This has attracted a lot of interest among both the researchers and industry. Special emphasis is placed on the fast manufacturing and the potentially very short energy payback time of OPVs [2–4]. An increase of several orders of magnitude for the operational lifetime of OPV has also been observed in recent years, with lifetimes reaching values beyond 1 year [5,6]. Considering the fast improvements in stability, the evaluation of the lifetime within a reasonable timeframe is becoming more and more challenging and this urges for the need of establishing methods of accelerated ageing that can reduce the testing time, yet provide an accurate estimate of the lifetime under real operational (outdoor) conditions [7–13].

The outdoor lifetime is influenced by the varying weather conditions throughout the year and thus the test conditions are of very fluctuating nature. For instance, summer provides more irradiation dose and elevated humidity, while in the winter the samples are subjected to reduced temperature and irradiances, strong wind and increased precipitation (rain, fog, and snow). Depending on the harshness of the climatic condition different lifetime results will be recorded at different geographic locations. Therefore, round robins and inter-laboratory collaborations have already been conducted a number of times with the aim to address and reveal such issues [14–17]. However a more systematic approach might be necessary in order to globally compare outdoor lifetime of OPV and further improve the lifetime prediction.

In 2011, the OPV research community proposed ISOS testing guidelines that describe how to carefully carry out stability tests of OPV samples under different test conditions in a reproducible manner [18]. The guidelines cover a wide range of tests stretching from simple shelf life or damp heat to sophisticated light soaking tests in weathering chambers and real outdoor tests. However, the question remained how to link such different tests to each other and establish acceleration factors among the real test conditions and more intense (accelerated) tests. The recent studies attempted to establish the degradation trends for OPV technologies with different device structures and encapsulations using under different ISOS tests [15–19]. The studies however were conducted only for indoor ageing.

The present study is a complimentary work that extends the previous studies to outdoor ageing conditions with an attempt to complete the comparative table of the ageing rates of ISOS tests with outdoor data. The present work proposes to use the

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established data as an initial step towards creating a tool for lifetime prediction based on accelerated tests.

2. Experimental

2.1. Sample preparation

The study involves both modules produced with full roll-to-roll (R2R) techniques and single solar cells fabricated by mini-roll coating and by spin coating. The structure of the samples used for this study is schematically presented in Table 1. The procedure of fabrication has been presented earlier [20,21].

We have deliberately chosen modules employing two different geometric dimensions and two different types of PEDOT:PSS configurations to increase the variation in intrinsic stability of the samples. The structure variations are presented in Table 2 [22,23]. Meanwhile, the spin coated and mini-roll coated samples were deliberately encapsulated using different methods shown in Table 3. Referring to the table, partial encapsulation means that the encapsulant covers the active area and only partially the terminals (without edge sealing). Full encapsulation means that the whole device is sealed including both terminals and edges [24]. The study exploits samples fully encapsulated with PET and glass for respectively R2R and spin coated samples, while full PET, partial glass and partial PET are employed for mini-roll coated devices.

The initial performance for the three types of samples was in the following range:

R2R modules 1.16–1.98%.
Mini-roll coated cells 0.72–1.3%.
Spin coated cells 1.3–2.24%.

Table 1
Structure of the tested devices.

	R2R modules	Mini-roll coated solar cells	Spin coated solar cells
Substrate	PET	PET	Glass+ITO
Electrode+electron transport layer (Flextrode)	Silver+PEDOT:PSS+ZnO	Silver+PEDOT:PSS+ZnO	ZnO
Active layer	P3HT:PCBM	P3HT:PCBM	P3HT:PCBM
Hole transport layer	PEDOT:PSS	PEDOT:PSS	PEDOT:PSS
Electrode	Silver	Silver	Silver
Encapsulation	Full PET (PF)	Full PET (PF)/partial PET (P)/partial glass (G)	Full glass (GF)

Table 2
Different types of the tested R2R modules.

	Type 1	Type 2	Type 3
Front PEDOT:PSS	Clevios FE T DK	Clevios FE T DK	Clevios FE T DK
Back PEDOT:PSS	Agfa 5010	Clevios FE T DK	Agfa 5010
Active layer size (cm^2)	*57*	*57*	*107*
Cells on module (nr.)	8	8	16
Tested samples (nr.)	3	3	3

Table 3
Different encapsulations employed with mini-roll coated and spin coated devices.

	Mini-roll coated (active area 1 cm^2)	Spin coated (active area 0.25 cm^2)	Tested samples (nr.)
Glass full (GF)		X	3
Glass without edge sealing (G)	X		2
Plastic full (PF)	X		3
Plastic without edge sealing (P)	X		4

2.2. Test conditions

The outdoor ageing followed the standard ISOS-O-1 for mini-roll and spin coated cells, and ISOS-O-2 for R2R modules [18]. The samples were placed on the sun tracking platform shown in Fig. 1. R2R modules were continuously measured in-situ, while mini-roll coated and spin coated solar cells were periodically moved indoor and measured under solar simulator (Metal Halide Lamp Solar Constant 1200). The tests started on May 17th 2013 and ended on December 3rd 2014.

2.3. Data processing

2.3.1. R2R modules

The outdoor measurements of 9 R2R modules were conducted for over 1 year with automated recording of *IV*-curves every 10 min (ISOS-O-2). Variations of sun light intensity, spectrum and air temperature resulted in strong fluctuations of the data and thus, filtering of the data was necessary. The data points were filtered according to the following steps:

1. Only measurements acquired with irradiance above 700 W/m^2 were considered in order to remove data points acquired during the night or unclear sky.
2. A moving average was extrapolated from the data, using 20 consecutive data points. Only data points that were close enough to the moving average were kept. For each data point an error $\boldsymbol{e}$ was defined:

$$e = \left(x_i - \bar{x}\right)^2$$

where x_i is the ith measurement and $\bar{x}$ is the mobile average. Only samples with an error smaller than n-times the standard deviation were considered. An empirical approach showed the best results using $n=50$.

3. Stability parameters were determined according to the ISOS guidelines – T_0, T_{80}, T_s, T_{s80}, E_0, E_{80}, E_s, and E_{s80} [18]. E_0 corresponds to the initial performance evaluated at the initial time T_0, while E_{80}

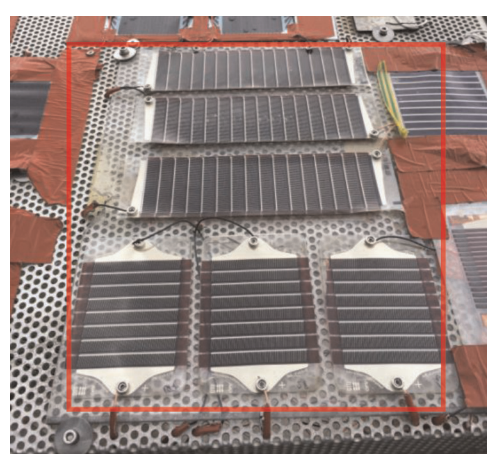

Fig. 1. The photo shows devices mounted on a solar tracking platform. The highlighted area indicates modules type 1 and type 3 which were connected to a Keithley digital multimeter for automatic measurements (ISOS-O-2).