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In-situ, long-term operational stability of organic photovoltaics for off-grid applications in Africa

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ABSTRACT

This paper presents a field-trial of organic photovoltaic (OPV) technology used within a practical application for rural electrification in Rwanda. Fourteen, large area, flexible, ITO-free, roll-to-roll processed OPV modules, encapsulated with low-cost materials, were installed on corrugated steel roofs at two sites in a rural village in Southern Rwanda and subject to continuous monitoring. This field-trial exposed modules to very high levels of insolation, in particular in the UV, high temperatures and heavy rainfall. Results show that the modules exhibit practical lifetimes (to degrade by 20% of their initial capacity) of between 2½ and 5 months, a value 5–6 times lower than control modules kept both in the dark and outdoors in Roskilde, Denmark. Degradation was primarily the result of extensive delamination caused by failure of the non-UV stable encapsulation, which led to decay in the FF, V_{oc} and I_{sc} of the module.

1. Introduction

Organic photovoltaics (OPV), based on polymer:fullerene blends, offer the potential for a scalable technology, produced through rapid roll-to-roll (R2R) processes, which can provide very low costs [1] and minimal environmental impacts [2]. Such devices have been studied extensively within academia and industry in recent years, leading to large gains in the efficiency of this technology [3]. However, in order to realise its full potential, the lifetime of modules must be improved. Considerable work has been done on building a greater understanding of degradation mechanisms and predictions of OPV lifetime [4–6], but this work has largely focussed on very small devices (often less than 1 cm^2), operating in laboratory conditions. Relatively few studies have looked at the stability of large area OPV modules under conditions which would be faced in practical applications [7–10]. This paper builds on the limited literature on the operation of large area modules within such practical applications.

One application where OPV technology may find a market is within off-grid photovoltaic systems powering small electrical loads. 1.3 billion people around the world have no access to modern forms of energy (of whom 600 million live in Sub-Saharan Africa) [11], and largely rely on inefficient and hazardous fossil fuels such as kerosene lamps for lighting. These forms of lighting must be replaced with modern solutions, most importantly for respiratory health and fire safety reasons [12] but also for an improved light quality and decreased financial burden [13]. In addition, the use of kerosene lighting creates substantial greenhouse gas (GHG) emissions [14,15]. It has been estimated that worldwide use of kerosene lighting produces 189 $MtCO_{2eq}$ annually (equal to the 28th highest emitting country) [16,17] and therefore represents a key application for GHG mitigation whilst also providing a host of ancillary benefits. Such an application requires a robust PV technology that can perform well under high temperatures, humid conditions, and dusty environments found in off-grid communities throughout Africa and Asia.

Studies on the outdoor degradation of OPV modules have, to date, focussed on Europe, and although a number of studies have reported performance in harsher conditions such as India, Israel and Ethiopia [9,18,19], these studies have looked at modules installed at laboratory sites rather than in real-world applications. The application of OPV technology in real-world conditions in Africa has been reported previously [20], although this study was limited by the difficulties of detailed data collection in such an environment.

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Here we present results of field trials of large area, roll-to-roll manufactured, ITO-free OPV technology using simple and low cost encapsulation operating under real-world conditions in rural Rwanda. This location presents an extreme environment where OPV may be used and thus the study provides an insight into the lifetime of OPV when used in such a real-world application. The sites in Rwanda demonstrate performance under challenging mounting conditions on uneven, corroded steel roofs, under high insolation, and heavy rainfall. This represents the first published report of the continuous monitoring of OPV technology in a practical application in a rural community in Africa.

1.1. *Outdoor degradation of OPV modules*

Analyses of the performance of OPV modules under outdoor conditions indicates the practical lifetime of OPV devices, although they do not always provide the most valuable insights for analysing specific degradation mechanisms. Such studies assess the module as a whole, rather than individual layers, and thus are equally an evaluation of the encapsulation as they are of the stability of the OPV materials themselves.

1.1.1. *Metrics for assessing degradation*

Stability analysis of OPV technology was standardised at the International summit on OPV stability (ISOS) [21]. These standards define what properties should be measured and how, as well as how to report results. These standards suggest that operational lifetime should be reported through the T_{80} metric, which quantifies the time for the performance of the device to fall by 20% from its initial, stabilised value. This metric therefore disregards any initial performance values prior to a period of rapid change in performance, such as due to a ‘burn-in’ period (for example improved performance after photo-annealing [22]). A second metric is also suggested, T_{s80}, which describes the time for the performance of the device to fall by 20% of that measured an interval T_s after fabrication.

1.1.2. *Degradation of large area ITO-free OPV modules*

This paper assesses the degradation of OPV modules based on an ITO-free architecture produced by the Technical University of Denmark (DTU). Modules used in this study (Fig. 1) have a device architecture which consists of: a Polyethylene terephthalate (PET) substrate; a cathode of high-conductivity poly(3,4-ethylenedioxythiophene) polystyrene sulphonate (PEDOT:PSS) combined with a grid of silver paste (Ag-grid); a zinc oxide electron transport layer; an active layer of a blend of poly(3-hexylthiophene) (P3HT) and Phenyl-C61-butyric acid methyl ester (PCBM); a PEDOT:PSS hole transport layer; and topped by an Ag-grid anode. The devices are manufactured according to the *Infinity concept* which uses flexo-graphic printing, rotary screen printing and slot-die coating to deposit OPV materials on a PET substrate, through a roll-to-roll process, and is presented in detail elsewhere [23,24].

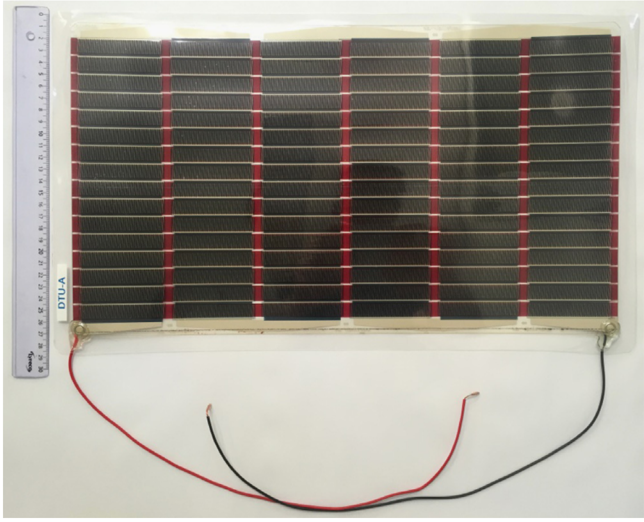

Fig. 1. Photograph of the OPV modules used in this study, showing both edge sealing and layout of electrical contacts in the module.

A number of studies have analysed degradation in very similar modules, which differ in size, encapsulation, and material used to contact the silver grid electrodes, which provide insights into the decay mechanisms seen in such modules [7–9,19,24–27]. It has been shown that the leading cause of degradation is due to ingress of atmospheric reactants from the edges of modules, and at the snap fastener (which is punched through the encapsulation). These reactants result in two principal degradation mechanisms being observed: photo-oxidation of the active layer, accelerated by oxygen, moisture and ozone formed by UV radiation; and delamination/degradation of the PEDOT:PSS layer due to moisture ingress which reduces conductivity and delaminates the weak bond between the PEDOT:PSS and active layer. Where photo-oxidation dominates, I_{sc} falls as the cells closest to the external contacts completely degrade, at which point they become resistors leading to a reduction in the V_{oc} and FF [9,25]. Degradation/delamination of PEDOT:PSS occurs more locally, allowing the V_{oc} to be maintained by small areas of all cells still being active, but reducing the FF. These mechanisms are greatly impacted by light levels, with active layer degradation being accelerated by high light levels, whilst water uptake by PEDOT:PSS is supressed in light conditions [8].

Larger borders of the encapsulation around the module can provide improved edge sealing, greatly reducing degradation [9,28]. In addition, modules have shown a large spread in the level of degradation, which has been suggested to be due to the manual contacting of the modules leading to different levels of wear and tear before installation [9]. Similar issues around mechanical stability of the devices, and the need for careful handling has also been highlighted in a previous trial of DTU modules in Zambia [20], suggesting that careful handling of the modules can also reduce degradation.

2. Method

2.1. *Organic PV modules*

Modules used in this field trial (Fig. 1) consisted of a roll of serially connected cells produced by the *Infinity concept* (in rolls of several hundred metres, see above), cut into lengths of approximately 50 cm, containing 96 serially connected cells in order to deliver a V_{oc} of around 45 V, the maximum voltage which would ensure electrical safety of the system. These modules were encapsulated using thin polymer layers which comprise a UV-filter and hard-coating. A secondary double-side edge lamination using standard hotmelt office lamination pouches (80 µm) was applied to mechanically protect the edge from delamination and therefore oxygen/water ingress, creating a 1–2 cm wide edge, resulting in the ratio of active area to encapsulation area of 58% (the geometrical fill factor, GFF). Hotmelt office lamination pouches were chosen due to their low cost, which is likely to be a key criterion for the technology in this application. Contacts were made by punching a snap button through the encapsulation and substrate, and contacting with the large area of silver printed on the substrate. Contact wires were then snapped into the button and covered in epoxy resin to seal the connection and avoid ingress of water and oxygen at this point in the module.

All modules in the trial, including control modules kept in Denmark, had already been exposed to at least half a year outdoors in Denmark before being taken to Rwanda.