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Five-year performance and reliability analysis of monocrystalline photovoltaic modules with different backsheet materials

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ABSTRACT

Elevated operating temperatures decrease the energy yield and reliability of photovoltaic (PV) systems. In order to minimize these thermal losses and stresses, different types of packaging materials for PV modules need to be examined with respect to their electrical and thermal performance but also their reliability and durability. This study analyses the performance and reliability of identical monocrystalline Silicon PV modules with different backsheet materials including aesthetically enhanced all-black PV modules employing black backsheets. The modules were installed to form grid-connected systems with an approximate nominal capacity of 1.2 kW_p, and were exposed under the warm climatic conditions of Cyprus. The results of the five-year evaluation period showed that despite the use of black backsheets, temperature improvements were achieved verifying that backsheets influence the cell temperature and enhance performance by operating at lower temperatures. More specifically, the comparative analysis of the thermal behavior, based on acquired cell temperature measurements, verified that backsheets can be designed to influence the cell temperature and enhance performance by operating at lower temperatures in some cases up to 10 °C. The systems with the backsheets that retained lower operating temperatures produced higher annual energy yield, under the warm conditions exposed due to reduced thermal losses. In particular, the annual energy yield results showed that the systems equipped with the white control and black color thermal management backsheet produced consistently the highest annual energy yield over the evaluation period. Finally, the results of the indoor and outdoor degradation rate analysis showed that, over the five-year period, there was no significant difference in the estimated degradation rate amongst the installed systems, since the results are within the uncertainty range.

1. Introduction

The geometry and thermophysical properties of the photovoltaic (PV) packaging materials, and especially the backsheet, have a direct impact on the thermal behavior of PV modules. It is well known that elevated operating PV cell temperatures affect negatively the energy yield of systems by decreasing the efficiency (Skoplaki and Palyvos, 2009). In addition to the thermal losses, PV systems that are subject to increased temperatures are prone to excess stresses that can influence the ageing, reliability and degradation of the device (Kurtz et al., 2011). Therefore, considerable efforts have been made for improving the thermal behavior and hence, the efficiency of PV systems by either modifying the geometry and packaging materials (Silverman et al., 2018; DeBergalis, 2004) or even by incorporating a cooling mechanism at the rear surface of the PV module (i.e. hybrid photovoltaic-thermal technologies, PV-T) (Hasanuzzaman et al., 2016; Ramos et al., 2017).

Furthermore, the rapid increase of PV installations in the building sector highlights the importance of taking into account other parameters, which are not considered in large PV power plants, such as the aesthetics of PV modules. PV modules with a uniform color maintain the architectural continuity and therefore are aesthetically preferable (Peng et al., 2011). Silicon-based PV technologies that account for over 90% of the installed capacity worldwide, are commonly fabricated using a white reflective backsheet whereas only a few companies exist on the market that manufacture PV modules with a black backsheet (Luxembourg et al., 2016). However, incorporating a black backsheet in a PV module comes at the price of higher operating temperatures since black surfaces absorb a greater amount of the incident solar irradiance that, eventually, is transformed into heat. Therefore, care must be taken into the geometry, thermophysical and optical properties of such backsheets, in order to enhance the heat rejection of PV modules. It is also crucial that PV modules employing new packaging materials are

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thoroughly tested not only for performance improvements but also for reliability purposes. The reliability of backsheet materials is currently tested under accelerated conditions according to the IEC 61215 qualification standard (Standard IEC 61215, 2005). Moreover, a number of backsheet components are also evaluated in terms of their suitability for PV module packaging applications, using indoor exposure reliability tests (Jorgensen et al., 2005; Gambogi et al., 2013). While indoor approaches may yield good results for infant mortality failures, it is generally accepted that in-depth information on the longer-term performance aspects can only be obtained from outdoor field studies.

Bearing these in mind, a five-year experimental campaign was conducted in Cyprus where the outdoor performance and reliability of PV modules employing different packaging components was evaluated under warm climatic conditions. Specifically, four grid-connected systems equipped with identical monocrystalline Silicon (mono-c-Si) PV modules but different backsheet materials were installed outdoors since 2012 in order to identify whether the packaging components can influence the performance and reliability of each individual system. Although the focus of this work lies on the usage of different backsheet materials that come with different thermophysical and optical properties, the primary driver for the study is the aspect of employing all-black color PV systems and in particular their potential in terms of enhanced thermal performance, greater energy yield and reliability.

2. Experimental setup

Four systems consisting of PV modules with identical mono-c-Si solar cells but different backsheet configurations (manufactured by Gebäude Solarsysteme GmbH) were installed at the outdoor test facility of the PV Technology Laboratory, University of Cyprus in Nicosia, Cyprus. The location's climate is classified as *BSh* by the Köppen-Geiger criteria (i.e. a hot semi-arid climate) (Peel et al., 2007). These systems were positioned in a landscape arrangement on aluminium mountings at the optimum inclination angle for Cyprus (i.e. 27.5°). The systems were installed side-by-side in a way that all modules are exposed to identical conditions that, in turn, would enable a reliable comparative analysis (see Fig. 1). In order to mitigate any location-dependent mechanisms of heat transfer (Goverde et al., 2015), also caused by wind effects (Farr and Stein, 2014), the same type of thermocouples were installed in identical positions and all modules were mounted in the same orientation and arrangement within a planar surface. Other PV modules were also installed at both sides in order to fill out the remaining open area of the planar surface. Each system consists of five PV modules connected in series to form a string, at the input of an inverter (SMA SB 1200) and their operational characteristics are being monitored since July 2012. The same inverters are used in order to exclude the influence of different maximum power point tracking (MPPT) algorithms (Makrides et al., 2013).

Fig. 1. PV systems installed at the outdoor test facility of the University of Cyprus (Makrides et al., 2013). All modules were mounted in an open rack, same orientation and arrangement within a planar surface. Additional PV modules were installed to fill out the remaining open area of the planar surface in order to allow identical exposure conditions.

The single-line diagram of a single PV system is shown in Fig. 2.

2.1. PV module backsheet technologies

The different backsheets were fabricated using polyethylene (PE), polyethylene terephthalate (PET) and fluoropolymer in the following configurations: (1) a typical heat reflective backsheet (with white on air-side/black cell-side backsheet), (2) a typical fluoropolymer white air-side/clear PET core/PE black cell-side backsheet (FPE), (3) a typical fluoropolymer white air-side/clear PET core/PE white cell-side backsheet and (4) a typical fluoropolymer black air-side/clear PET core/fluoropolymer (FPF) black cell-side backsheet. The typical fluoropolymer refers to Tedlar® Polyvinyl Fluoride (PVF) films while the typical heat reflective backsheet was fabricated by incorporating materials in order to reflect as much of the Infrared Radiation (IR) as possible, minimize absorption by the backsheet and to reduce the resulting overall module rate of temperature rise as well as the peak temperature. The primary mechanism was the use of IR reflective pigments and additives incorporated into the sun-facing dark layer of the backsheet. In addition, the heat-reflective additives were thermally stable and inert in order to not affect other module components in any way, regardless of any variance in lamination conditions. The heat reflective backsheet comprises of two additional layers. The first layer has a reflectance greater than 25% from around 1000 nm to 2100 nm and a reflectance lower than 35% from around 380 nm to 750 nm while the second layer has a reflectance greater than 50% from around 380 nm to 2000 nm. Furthermore, there were no differences in the processing procedures of the different backsheets, in order to not affect the cells or metallization. Front and rear view images of each type of PV module are illustrated in Fig. 3.

The details of the backsheet materials are summarized in Table 1.

The rated power of the PV modules under investigation ranges from 245 W_p to 252 W_p and the electrical characteristics of the open-circuit voltage, (V_{OC}), short-circuit current (I_{SC}) and others at Standardized Test Conditions (STC) (i.e. global irradiance of 1000 W/m^2, cell temperature of 25 °C and air mass of AM 1.5G) are outlined for each system in Table 2. The operation of the four types of PV systems was monitored through a data-acquisition platform. The platform comprises of meteorological, irradiance and electrical sensors connected to a central data logging system that stores data at a resolution of one second and stored accumulation steps of one- and fifteen-minute averages. Specifically, the irradiance and meteorological measurements include the plane-of-array global irradiance (G_{POA}), wind direction (W_a) and speed (W_s), as well as ambient temperature (T_{amb}). The electrical measurements include maximum power point (MPP) DC current (I_{MPP}) and voltage (V_{MPP}) and DC and AC power (P_{MPP}) as measured at the output of each PV system.

In addition, three K-type thermocouple sensors were embedded in each module for the acquisition of cell temperature (T_{cell}). Such measurements allow the comparison of the thermal behavior of each type of backsheet in order to provide performance advantages especially under warm climatic conditions. More specifically, the thermocouple sensors were installed at three different locations of each PV module, as shown in Fig. 4. The comparative analyses in this study report on the mean system temperature by averaging all the cell temperature measurements within an individual PV system.