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Differential degradation patterns of photovoltaic backsheets at the array level☆

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ABSTRACT

There are relatively few field studies on the degradation of non-fluoropolymer-based backsheets, and understanding their in-field behavior is critical for further development of such products. In this study, backsheet degradation of modules with one of these new types of backsheets (polyethylene naphthalate (PEN)-based) was documented at a four-year old utility-scale array located in Maryland (USA). Visual inspection, colorimetry, glossimetry, and Fourier-transform infrared spectroscopy (FTIR) revealed highly varied properties depending on module position within the array. Specifically, modules near the edge of the array and with higher mounting elevations underwent greater amounts of backsheet degradation, as indicated by yellowing and gloss-loss. The reason for these unique degradation patterns were differential backside exposure conditions, especially of ultraviolet light. This was strongly influenced by the array design, including array structural and environmental factors, such as module spacing and ground cover, respectively. Within the array, no clear link between backsheet degradation and module output or safety has been identified. However, such a relationship may be expected to become more pronounced with time, affecting system lifetime and ultimately the levelized cost of electricity (LCOE). The observed phenomena have implications for both backsheet product development and array design, especially for modules that utilize newer classes of non-fluoropolymer-based backsheets which are typically more susceptible to environmental degradation.

1. Introduction

Backsheets serve a crucial role in the safe operation of photovoltaic (PV) modules, acting as both a weathering barrier and electrical insulation for the backside of solar cells (Gambogi et al., 2013; Köntges et al., 2014; Oreski and Wallner, 2005; Voronko et al., 2015). Backsheets are typically polymer laminates consisting of a weather-resistant outer layer, an electrically insulating core layer, and an inner layer which promotes adhesion to the solar cell encapsulation. During outdoor exposure, polymeric materials tend to degrade and lose their functionality, which makes the selection of a backsheet for PV modules an important design consideration, especially with the ≥25 year warranties from many manufacturers*(Jordan and Kurtz, 2013). Therefore, considerable effort must go into understanding backsheet degradation mechanisms, how degradation influences module performance and safety, and ultimately how to predict the service life of polymeric backsheets (Bruckman et al., 2013; Lin et al., 2016; Oreski and Wallner, 2005; Osterwald and McMahon, 2009; Voronko et al., 2015). These are all significant elements for determining warranty periods and the levelized cost of electricity (LCOE) of a system.

The backsheet market is currently dominated by fluoropolymer-based outer layer materials, such as polyvinyl fluoride (PVF) and polyvinylidene fluoride (PVDF), which tend to withstand weathering and fulfill their functional purpose even after 20 years (Bradley et al., 2015; Gambogi et al., 2013; Oreski and Wallner, 2005). However, continued pressure on manufacturers to reduce module cost has led to the development of lower cost non-fluoropolymer-based backsheets, such as those based on polyester or polyamide outer layer materials. The drawback of non-fluoropolymer-based materials is that they must be modified (e.g., by additives) to withstand weathering, and even with

☆ Certain commercial equipment, instruments, or materials are identified in this work in order to adequately detail the experimental procedure. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials and equipment identified are necessarily the best available for this purpose.

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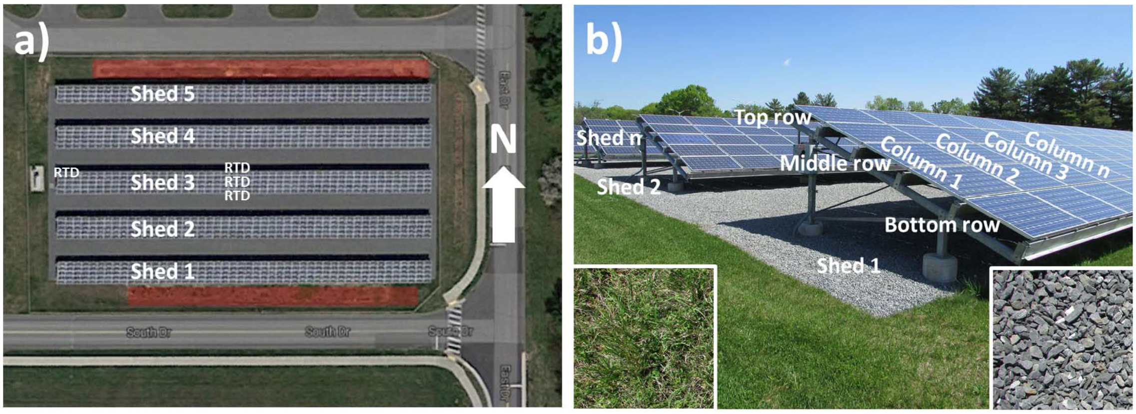

Fig. 1. Layout of the NIST ground-mounted PV array (Google Maps, 2016) (a), and orientation of the modules within the array, including nomenclature labels utilized in this work (shed-row-column) (b). "RTD" in (a) marks the approximate location of modules where backside temperature was recorded, and red boxes show the locations of the bio-retention areas (refer to the online color version). Insets for (b) show the ground cover at the array, including grass and coarse rock.

modification, they may still be more susceptible than fluoropolymers (Bradley et al., 2015; Gambogi et al., 2013; Lin et al., 2016; Oreski and Wallner, 2005). Additionally, because of their more recent commercialization, there are relatively few field studies and a lack of widely accepted testing criteria to help predict their service life. Of the newer outer layer backsheet materials, those based on polyesters such as polyethylene terephthalate (PET) are among the most prominent. Polyethylene naphthalate (PEN), polypropylene, polyimide, and polyamide-based materials are also being considered as potential candidates. Collectively, non-fluoropolymer backsheets constituted nearly 60% of the global backsheet PV market by area in 2014 (Global Market Insights, 2017).

During outdoor exposure there are three main environmental stressors that affect polymer degradation: temperature, humidity, and light (especially ultraviolet (UV)) (Bruckman et al., 2013; Day and Wiles, 1972; Lin et al., 2016; McMahon et al., 1959; Oreski and Wallner, 2005). Additionally, transitory and cyclic variations of these stressors (diurnal, seasonal) can play a role by the addition of thermal-mechanical stresses. Previous field studies tend to focus either on module performance or frontside degradation, and document effects such as power loss, soiling, cell damage, metal contact corrosion, encapsulant discoloration, and frame corrosion (Dechthummarong et al., 2010; Djordjevic et al., 2014; Felder et al., 2014; Gambogi et al., 2015; Hasselbrink et al., 2013; Lopez-Garcia et al., 2016; Quintana et al., 2002; Sánchez-Friera et al., 2011; Skoczek et al., 2009). Comparatively little focus is placed on the backsheets, perhaps because backsheet failure tends occur very late, near the end of the module lifetime, at least for modules with fluoropolymer-based backsheets (i.e. nearly all > 20 year old field-exposed modules).(Köntges et al., 2014) However, this newer class of non-fluoropolymer-based backsheet materials may perform differently over the life of a PV module, and greater scrutiny on backsheet degradation and its effect on module performance and safety is needed. From surveys reporting on backsheet properties, the main degradation and failure indicators include discoloration, delamination, cracks, and burn-marks (from solar cell hot spots).(Dechthummarong et al., 2010; Dunlop and Halton, 2006; Felder et al., 2014; Gambogi et al., 2015; Kato, 2011; Sánchez-Friera et al., 2011) These have the potential to accelerate module degradation, e.g., by allowing liquid moisture ingress which can accelerate corrosion of solar cell metallization (Jaeger et al., 2013; Kempe, 2006; Peike et al., 2012). These failure modes can also pose safety hazards, e.g., by exposing high-voltage discharge points (Dechthummarong et al., 2010; Gambogi et al., 2015; Köntges et al., 2014; Quintana et al., 2002). Ultimately, either of these factors – reduced output and increased safety risks – affect the service life of a module. Therefore, mitigating backsheet degradation is one necessary component of improving PV module reliability and extending module lifetime beyond 25 years to make the LCOE more competitive with conventional power sources such as coal, gas, or nuclear plants, which have > 40 year lifetimes (Tidball et al., 2010).

This work presents results and analysis from a field study of PV module backsheet degradation at a ground-mounted array at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland (USA). It is a small utility-scale array installed in August 2012 that consists of 1152 modules having a rated power of 271 kW. The modules are based on front-contact, monocrystalline silicon solar cells, and utilize a PEN-based backsheet. Within the array, significant differences were observed in backsheet degradation characteristics, including color, gloss, and chemical analysis. These differences were shown to be due to gradient exposure conditions that exist within the array, arising from array structural and environmental factors including module location, elevation, and ground cover. In particular, backside UV exposure was found to vary the most and was suspected to cause the observed differences between the backsheets.

2. Materials and methods

2.1. Site and array overview

The ground-mounted PV array is located at the main NIST campus in Gaithersburg, Maryland (USA), with coordinates 39° 07′ 54.7″ N; 77° 12′ 50.8″ W, and an elevation of 136 m. The area has a hot, humid continental climate (Dfa in the Köppen-Geiger classification), which is characterized by a hot summer, and no dry season (Peel et al., 2007). There are 1152 modules (Sharp NU-U235F2) at the site, installed in August 2012, with a total rated DC power of 271 kW (Boyd, 2017). The array is situated on coarse, gray rock (#57 stone, likely granite), and bordered by grass and bio-retention (storm water collection) areas, as seen in Fig. 1. It is divided into five sheds, each with five rows of modules in 48 columns, as shown in Fig. 1b (except shed 5, which contains four rows of modules). The modules are oriented due south at 20° to the ground, and the center-height of the top, middle (third row from bottom), and bottom row modules is approximately 2.2 m, 1.5 m, and 0.9 m, respectively (for shed 5-top row it is 1.9 m). This figure also shows the nomenclature utilized throughout this work (shed-row-column).

2.2. Backsheet properties

Backsheet degradation was monitored using non-destructive techniques, including visual inspection, colorimetry, glossimetry, and Fourier-transform infrared spectroscopy (FTIR). These inspections were made on 24 October and 18 November 2016, corresponding to just over four years of outdoor exposure. Weather on those days was mostly