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Soiling and cleaning: Initial observations from 5-year photovoltaic glass coating durability study

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ABSTRACT

The contamination of solar photovoltaic cover glass can significantly reduce the transmittance of light to the surface of the photovoltaic cell, reducing the module's power output. The solar industry has been developing antireflection (AR) and antisoiling (AS) surface coatings to enhance light transmittance and mitigate the impacts of soiling. Although uncoated glass has been field tested for decades, minimal data exist to demonstrate the durability of AR and AS coatings against abrasion and surface erosion, including from: natural weathering, airborne sand, and industry cleaning practices. Coupons 75 mm square of varying types have been field-deployed to gather long-term data on coating durability; the initial results are presented here after 1 year of outdoor exposure near Sacramento, California. Duplicate sets of coupons were cleaned monthly per four different cleaning practices. All coupons demonstrated inorganic soiling as well as microscale biological contamination, regardless of cleaning method. Additionally, full-sized, field-aged modules from other areas of the world presented with similar types of contamination as the field-aged coupons; micrographs and results from genomic sequencing of this contamination are included here. Optical microscopy, scanning electron microscopy, atomic force microscopy/energy-dispersive spectroscopy, surface roughness, transmittance, and surface energy analysis of representative specimens and cleaning practices are presented.

1. Introduction

Solar photovoltaic (PV) module technology is projected to increase to the terawatt scale in the coming years [1]. Although numerous PV technologies continue to approach their theoretical Shockley-Queisser conversion efficiency limit, all technologies are susceptible to performance losses over time due to numerous failure modes, including cover-glass degradation [2]. One type of cover-glass degradation is soiling, or the deposition of ambient particulate matter (PM) onto the surface of solar glass. Losses due to soiling depend strongly on location, because ambient particulate matter is generated by both natural and anthropogenic sources and can vary due to factors such as climate, seasonal changes, soil composition, and proximity to industrial activities [3]. PV power losses from soiling have been reported from single-digit percentages to as high as 70% depending on the world location, often having a higher impact on annual PV performance than cell degradation [4–13]. Annual soiling losses in California have been observed to be in the 4%–7% range [2,5,6,14]. Some of the concepts and findings in this study may be applied to other solar technologies, including concentrated solar power (CSP) [15].

The expected composition of soiling on the surface of PV modules will vary with the airborne particulate matter generated by both local and distant sources. Generally, soiling is primarily composed of silica particulates and the metal oxides commonly found in the Earth's crust. It can also include air pollutants such as soot, salts, and sulfuric acid particulates, the latter of which can be formed by gas-to-particle conversions in the atmosphere. Finally, biofilms, likely deposited onto the surface of a module as biological aerosols, can grow on solar glass [16]. Fungal and algal biofilms have previously been found on solar modules deployed in Sao Paulo, Brazil, that showed a 7% power loss within a 1-year period [17]. Biofilms are thought to interact and bind with the substrate in many ways, secreting organic acids and other compounds that may contribute to weathering and absorbing and scattering light [18]. Biofilm communities have been shown to work together to retain water and ambient particulates to satisfy their need for nutrients [19].

Currently, there is no systematic mitigation strategy for the soiling

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problem. It is common to monitor the degradation in system power output (due to soiling) and then to clean the modules when the economic gains outweigh the cost of cleaning [20]. Cleaning frequencies and methods depend on several factors, including the installation location. For example, in locations with regular rainfall, the system owner might rely solely on natural cleaning. In the southwest United States, there can be dry periods lasting 3–9 months, where the system owners perform 1–2 cleanings during these times. Water cleaning (by either pressurized spray or wet brushing) is typical in the southwest United States. In desert regions of the Middle East, where water is scarce or expensive, dry cleaning with a brush is often used. Various types (both wet and dry) of automated cleaning robots are also being introduced to the marketplace. Standard solar modules with a glass front have been deployed in various field conditions for decades. Therefore, solar glass is generally accepted as sufficiently durable to cleaning practices. In recent years, surface coatings have been applied to solar glass, but it is not known how durable these coatings are to natural weathering or cleaning. For example, many manufacturers now include AR coatings on the glass surface to boost module performance on the order of 3% [21]. In response to the soiling problem, there is significant effort underway to develop AS coatings or surface functionalizations that will help maintain clean module surfaces [22–25]. With the advent of these coatings, it has become an industry priority to develop standardized durability testing to determine if coatings will be economically viable under various field environments or cleaning practices [21].

The National Renewable Energy Laboratory (NREL) is currently working with industry to develop standardized durability test methods for surface coatings for PV modules. As part of this work, a 5-year field experiment is underway to collect coating degradation data from the field. The primary goal of the study is to collect abrasion and damage data to validate accelerated abrasion tests. Multiple coating types as well as baseline solar glass have been deployed at five challenging world locations. Various options for cleaning the coatings are being studied systematically to represent normal industry practices, including: 1) no clean, 2) low-pressure wet spray with no mechanical contact, 3) wet sponge wipe followed by a squeegee, and 4) dry brushing. This protocol is also expected to provide insight about the abrasion due to cleaning practices, natural weathering damage, the mechanisms enabling soiling, site-specific soiling differences, and the performance and durability of the different coating types. This paper presents selected results from the first set of samples that were collected after being deployed in a rural area bordering Sacramento, California, for 1 year. Results will also be compared to specimens obtained from a module deployed in Argenbühl, Germany, for 6 years and Palms, California, for 11 years.

2. Methods

In this study, ten types of 75-mm × 75-mm coated or uncoated samples—or "coupons"—were deployed to weather for 1–5 years in or near the cities of Sacramento, California; Tempe, Arizona; Dubai, U.A.E; Mumbai, India; and Kuwait City, Kuwait. Each location represents a unique climate and soiling potential (Table 1): the Sacramento location is in an agricultural area with the potential for a long dry season as well as wetter periods; the Tempe location is east of Phoenix in a suburban environment near the dry Arizona desert; the Mumbai location is an urban environment and is known for a long dry period and a monsoon season; the UAE location is in the desert south of Dubai where frequent coastal dew cycles occur; finally, the Kuwait city location is a dry desert environment with a high frequency of sandstorms. Also included in Table 1 are two locations where full-sized PV modules were aged; some observations regarding those modules are reported in this paper.

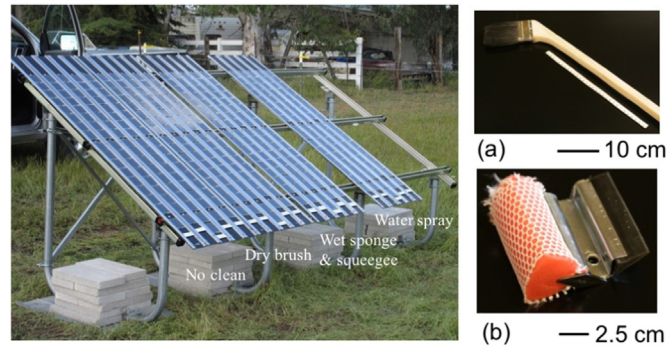

Fig. 1. A 30-degree tilt rack with 20 coupon holders (each holding seventeen 75 mm × 75 mm coupons) as deployed outside Sacramento, California in April 2016. From left to right, the first coupon holders are never cleaned; the coupons in the next five holders are dry brushed monthly, the next five are rubbed with a wet sponge followed by a squeegee monthly, and the last five are water sprayed monthly. One coupon holder is removed from each set of cleaning methods each year and returned to NREL for each of the 5 years in the study. (a) shows a representative brush (with horse hair bristles) used for dry brush cleaning; (b) shows a representative head for a squeegee used with water.

The coupons are mounted on racks at a 30-degree tilt in Sacramento, Tempe, and Kuwait City, whereas they are inclined at 25 degrees in Dubai and 19 degrees in Mumbai. All racks are installed on the ground except for Mumbai, which is on a rooftop within the city. Fig. 1 is an image of the coupons as installed in Sacramento, California, and they are the first samples to achieve a year in the field; therefore, they are the focus of this paper.

The coupons (see Fig. 1) in this study are 75 mm × 75 mm and are all coated or uncoated float glass substrates except for one plastic sample, poly(methyl methacrylate) (PMMA), which is representative of lenses that have been used in concentrator PV modules. NREL provided Diamant 3.2-mm-thick, low-iron float glass (by Saint-Gobain S.A.) to various collaborators in the coating industry as a common substrate material. One coating manufacturer instead used 3.2-mm-thick Optiwhite float glass (Pilkington Group Ltd.) as the substrate material. To have a comparison to the coatings, uncoated Diamant and Optiwhite glass coupons were deployed. Because solar modules typically have tempered glass, a set of heat-tempered, uncoated Diamant glass

Table 1
Coupon deployment locations, respective climate classifications, PM2.5 concentrations, dust storm, and precipitation information [26–28]. PM2.5 represent estimates of the average ground-level concentration (in μg/m^3) of fine particulate experienced in 2015 by each site. These data have been extracted from the 0.1-degree × 0.1-degree resolution database developed by [29].

Deployment Location: City, State (Country)	Köppen Climate Classification	General Climate Type	Average PM2.5 (mg × m^{-3} × y^{-1})	Number Dust Storms (y^{-1})	Annual Precipitation (mm)
Sacramento, CA (USA)	Csa	Mediterranean	14.9	0	464
Tempe, AZ (USA)	BWh	Hot desert	12.6	4	204
Mumbai (India)	Aw	Tropical wet & dry	52.5	0	2258
Dubai (UAE)	BWh	Hot desert	86.4	4	94
Kuwait City (Kuwait)	BWh	Hot desert	70.8	21	116
Argenbühl (Germany)	Cfb	Temperate oceanic	10.0	0	1159
Palms, CA (USA)	Csa/Csb	Mediterranean	10.5	0	379