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A new method to determine the effects of hydrodynamic surface coatings on the snow shedding effectiveness of solar photovoltaic modules

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ABSTRACT

As solar photovoltaic (PV) installations have become more common in regions that experience substantial snowfall, losses in energy production due to snow coverage have grown in concern. Several post-production surface coatings have been proposed to enhance snow shedding to reduce these snow related losses. In this paper, a novel methodology is developed to determine the effectiveness of a snow clearing from a PV module and is used to evaluate the snow shedding effectiveness of any module surface treatment. Measured PV output is compared to modeled PV output in a generalizable method that allows for the determination of the length of time a panel is covered with snowfall using electrical performance data. This model accounts for module degradation during long-term outdoor testing and other external factors effecting performance, such as persistent soiling losses. This methodology was tested on modules that had one of four hydrodyanmic surface coatings, as well as one module with a prismatic glass front in order to determine the snow clearing effectiveness of these surfaces as compared to conventional plain glass. The methodology was validated, but the surface coatings tested did not have an appreciable positive effect on snow clearance, and in some cases tended to impede the shedding of snow. The physical mechanisms responsible for the results are discussed.

1. Introduction

Solar photovoltaic (PV) technology is becoming financially competitive in a growing number of jurisdictions worldwide [1], and government incentives for sustainable technologies are enabling PV to be competitive in regions where the technology has not yet reached grid parity with subsidized traditional generation. This has lead to the installation of PV in regions exposed to snowfall in the winter months, which can lead to losses in energy generated due to snow coverage [2–4]. It has been shown in the past that hydrodynamic coatings can improve the clearance of ice from glass surfaces [5–10], but no previous methodology was successful to account for potential energy gains related to improved snow removal from PV modules due to hydrodynamic coatings. This work provides a methodology and preliminary results that investigate the effectiveness of hydrodynamic coatings and surface treatments on the clearing of snow from PV modules. The methodology presented utilizes time-series performance data and time lapse photography to identify snow clearing effectiveness of a surface coating. A concern with using this long-term performance data is the uneven degradation of PV modules over a test campaign, and a method for accounting for these effects while avoiding the requirement of regular flash testing is presented.

2. Background

Previous work has investigated the effects of snowfall on the performance of PV systems [2,11–16], and the results of these investigations have been summarized and expanded by the authors in recent publications [3,4]. From these studies it has been observed that snowfall can degrade the production of PV systems, and therefore it is desirable to investigate methods to effectively clear modules of snowfall to maximize solar electric yearly output.

The accumulation of ice on surfaces has been extensively studied mainly with the goal to reduce ice accumulation on power infrastructure, aircraft surfaces, wind turbine blades and other industrial surfaces. As such, hydrophobic and superhydrophobic coatings have been tested for their icephobic properties. Previously, the crystallization time onto a coated surface [17–20] or the shear stress required for ice detachment [5–10] have been considered as measures of icephobicity. It was found that the contact angle (CA), which is generally used as a measure of hydrophobicity is not a reliable indicator of icephobicity. However, the contact angle hysteresis (CAH) was found to correlate well with icephobic properties [5–7]. The CAH is defined as the

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difference between the advancing (θ_{adv}) and receding (θ_{rec}) contact angles, and is also analogous to the angle at which a stationary droplet will begin to slide (α_{slide}) through [21]:

$$\frac{mg}{w}\sin(\alpha_{slide}) = \gamma_{LV}(\cos(\theta_{rec}) - \cos(\theta_{adv})) \tag{1}$$

where m is the mass of the water droplet, w is the width of the drop perpendicular to the sliding direction, g is the gravitational constant, and γ_{LV} is the liquid–vapor surface tension. Further, it was noted that the dimensionless factor $[1+\cos(\theta_{rec})]$ scales linearly with the CAH and can also be used as a predictor of icephobicity [10]. Thus the three terms: CAH, α_{slide}, and $[1+\cos(\theta_{rec})]$ can be utilized as predictors of icephobicity.

The interaction of water droplets with a surface was also found to have an impact on its icephobic properties, which can be described generally by two states of wetting: the Wenzel or Cassie–Baxter state. The Wenzel state exists when water has penetrated the surface roughness of the coating, and the Cassie–Baxter state is observed when air is trapped between the water and asperities (roughness) of the surface coating and is associated with improved icephobic properties [6]. In the case of humidity or high droplet impact velocities, the state can be changed from the Cassie–Baxter to Wenzel state, which will decrease the icephobicity of the surface for a particular surface coating [7].

Surface roughness is integral to the hydrophobicity of many non-nano-structured coatings; however, it has been found that through a series of freeze-clear events, the hydrophobicity of a surface will be decreased as asperities are damaged through the expansion and contraction of water in the coating [5,7,8]. Thus, nano-structured hydrophobic coatings are predicted to have improved icephobic performance due to their improved durability during freeze-clear cycles, and their predicted promotion of freezing in the Cassie–Baxter state [10].

There has been a limited amount of work to extend the concepts of icephobicity to snow clearing effectiveness. However, it has shown that the hydrodynamic behavior of a surface will affect the adhesion and sliding of snow in a variety of ways that depend on the water content of the snow cover. Specifically, it was found that a hydrophilic surface will tend to promote the sliding of a "wet" snow sheet, which is defined as snow *above* the temperature of −1 °C to −2 °C [22]. In this case the hydrophilic surface will tend to attract the water in the snow and form a lubricating water layer at the surface of the glass that promotes snow sliding. For a hydrophobic coating, the surface will tend to resist the adhesion of snow, and will not promote the forming of a water layer. Therefore, wet snow will not as easily shed from the hydrophobic surface. However, because of the lower adhesion of snow and lower surface energy of the glass, "dry" snow defined as snow formed *below* −1 °C to −2 °C will shed preferentially from this surface [22]. The tendency of snow to adhere to a surface has also been studied and it was shown that a hydrophobic surface will tend to decrease the likelihood of snow adhesion, whereas a hydrophilic coating will increase the probability of this adhesion [23]. For the application to PV in regions where snow exists and the temperature varies around the −1° to −2° switch point, the determination of optimal surface properties is complicated. This paper presents a generalizable method to make this determination for any PV and surface coating.

3. Methodology

A test system was installed at the Open Solar Outdoors Test Field (OSOTF) in Kingston, Ontario Canada. This site was developed based on open-source principles, and consists of solar PV modules of mono–poly-crystalline silicon (c-Si) and hydrogenated amorphous silicon (a-Si:H) installed at tilt angles of 5°, 10°, 15°, 20°, 40°, and 60° [24]. For this study sixteen c-Si modules at angles of 10°, 20°, 40° and 60° were used, with each angle consisting of four modules, with the following surface treatments: hydrophobic, hydrophilic, prismatic glass, and one unaltered module. Nine a-Si:H modules were installed at angles of 10°, 20°, and 60° and each angle consisted of a total of three panels with the following surface treatments: two hydrophobic coated modules and one unaltered module. This facility was monitored over the winters of 2010/2011 and 2011/2012. Table 1 shows a summary of the installed modules, and a description of the coatings and coating methodology used is provided below.

3.1. Crystalline module coating

The coatings used on the c-Si modules were nano-structured, bonded covalently to the surface of the glass, and formed a layer 10–30 nm in thickness. The modules were first cleaned using a commercially available window cleaner. The coating was then applied evenly over the surface of the module using an application wand, and was then buffed into the glass surface using a microfibre cloth. Modules coated with the hydrophobic (ho1) treatment were then rinsed to remove excess solvent. The hydrophyllic (hy) coating was cleaned using the same commercially available window cleaner to remove excess solvent.

Table 1
Module index reference, *c* represents crystalline and *a* represents amorphous. (ho1)…(ho3) represent hydrophobic coatings, (hy) represents a hydrophyllic coating, (prism) represents a prismatic glass front surface and (C) represents a control module.

c-Si		a-Si:H	
Module Index-technology-(coating)	Module angle (deg)	Module Index-technology-(coating)	Module angle (deg)
1-c-(C)	10	1-a-(C)	10
2-c-(hy)	10	2-a-(ho2)	10
3-c-(ho1)	10	3-a-(ho3)	10
4-c-(prism)	10	4-a-(C)	20
5-c-(C)	20	5-a-(ho2)	20
6-c-(hy)	20	6-a-(ho3)	20
7-c-(ho1)	20	7-a-(C)	40
8-c-(prism)	20	8-a-(ho2)	60
9-c-(C)	40	9-a-(ho3)	60
10-c-(hy)	40		
11-c-(ho1)	40		
12-c-(prism)	40		
13-c-(C)	60		
14-c-(hy)	60		
15-c-(Prism)	60		