Enhanced Photovoltaic Soiling In An Urban Environment

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***Abstract* — Natural soiling, or the deposition of ambient particulate matter (PM) onto the surface of solar glass, causes losses in PV production around the world. Much work in the PV community has focused on soiling in dusty desert environments. However, PV systems in urban environments are exposed to different contaminants and thus soil differently. We present an analysis of PV soiling in such an urban environment considering the impacts of meteorological parameters. We present 1 year of results from a soiling station in an urban location in Colorado. Bare glass samples were exposed outdoors for 11 days alongside the station; results from microscopy and light transmittance measurements show how moisture and dew affect the morphology and optics of contamination on glass. The coupon results suggest that natural (rain) cleanings may not be sufficient to clean solar panels in urban environments. Ion chromatography of soiling on the reference cell surfaces suggest that dry brush cleanings may not sufficiently clean chemicals deposited on solar panel surfaces in urban environments.**

***Index Terms* — solar energy, solar panels, soil, photovoltaic cells.**

I. Introduction

Solar photovoltaic (PV) module technology is projected to increase to the terawatt scale in the coming years [1]. Natural soiling, or the deposition of ambient particulate matter (PM) onto the surface of solar glass, causes losses in PV production around the world. Losses due to soiling depend strongly on location, because PM is generated by both natural and anthropogenic sources and can vary due to factors such as climate, weather, seasonal changes, soil composition, and proximity to industrial activities [2]. In the United States, annual PV power losses from soiling have been reported to be as high as 6%, a higher impact on annual PV performance than cell degradation [3]. Investigation into PV soiling has grown in recent years along with the increased prevalence of the technology, and a more recent topic gaining attention is the effect of dew cycles on soiling; it is possible that the wetting of the glass surface resulting from dew formation enhances the retention of soiling [4]–[6].

Particles attach to surfaces through dry and wet deposition; dry deposition occurs constantly whereas wet deposition is an episodic phenomenon. In dry deposition, the dominant mode of deposition onto surfaces is Brownian diffusion for smaller particles and inertial or gravitational impaction for larger particles. In wet deposition, water droplets form via water vapor condensation onto ambient particulate matter; once these droplet-particle combinations achieve a critical mass, they fall as precipitation [7]. Depending on the amount of total precipitation experienced at the PV site, precipitation can either enhance or detract from the soiling level [3], [8]. This is potentially due to three mechanisms: first, precipitation falls onto the PV surface and washes away contamination; second, moisture on the surface enhances the deposition of soluble and chemically reactive gases such as sulfur dioxide and nitric acid; third, water on the surface evaporates in dry conditions leaving behind the particulate nucleus and a solute ring around the edge of the droplet.

The variation in soiling levels at sites across the US is not currently well understood. The state of Colorado, for example, is assumed to be a very low-soiling region relative to the dusty deserts of Arizona and California. However, soiling is dependent on local micro-environments. This project aims to quantify the soiling losses at an urban location in Colorado and understand how dew affects urban PV soiling in an assumedly low-soiling state.

II. Methods

A. Soiling Station

A soiling station built at the National Renewable Energy Lab (NREL) in Golden, Colorado was deployed on February 14, 2018 at a Colorado Department of Public Health and Environment (CDPHE) meteorological station in Globeville, Colorado (Fig. 1). The soiling station consists of a small solar panel, two reference cells, a brush and motor, and other ancillary equipment. Data is logged remotely via cellular modem. The brush automatically activates once per day in the morning, sweeping one of the reference cells. The soiling station was deployed there in order to co-locate with the high quality meteorological and air quality instrumentation at the CDPHE site.

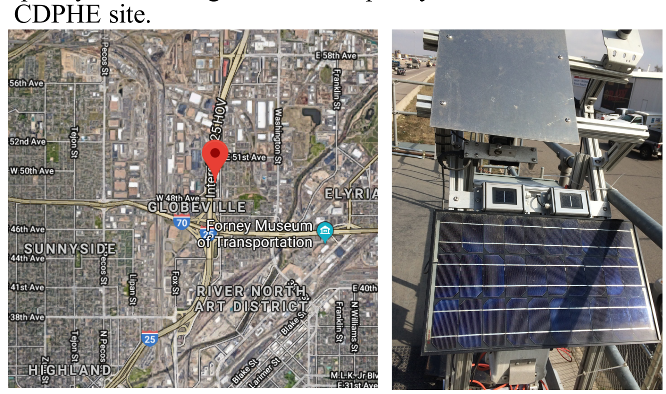

Fig. 1. Left: satellite imagery (provided by Google 2018) of the location, showing highways and industrial surroundings. Right: a photo of the soiling station on top of the roof of the CDPHE meteorological station.

The CDPHE collects minute-level data for parameters including ambient PM10 and PM2.5 concentrations, wind speed, wind direction, relative humidity, and ambient temperature. The soiling station collects soiled and unsoiled reference cell irradiance as well as reference cell temperature. Outside of utilizing the temperature and relative humidity levels to identify dew occurrences, analysis of the air quality data is not included in this report.

The irradiance data was analyzed using a modified version of NREL's stochastic rate and recovery (SRR) algorithm [9] to identify soiling intervals of interest for the study. The data is first filtered to only include times +/- 1 hour from local solar noon. Then, only data above 700 W/m^2 was retained in order to reduce the effect of clouds and inclement weather. Daily averaged "soiling ratio" (SRatio) is obtained by dividing daily uncleaned irradiance by cleaned irradiance. The SRR method was originally developed for yield data and is is described in detail elsewhere [9]. Here, we have adapted it to operate on SRatio data. First, a five-day rolling median SRatio was calculated extrapolating between missing data. Positive shifts in the rolling median are interpreted as cleaning events. A "soiling rate" (SRate) is extracted using the Theil-Sen statistical fitting method for each soiling interval. Overall SRate is calculated as the median SRates for all valid dry periods, and overall SRatio is obtained as the average of the SRatio values [10].

The following equations were used in order to calculate the dew point temperature based on the ambient temperature and relative humidity; α and b represent the Magnus parameters of 17.271 and 237.7, respectively [6]. Dew is assumed to be present on the surface of the solar glass when the temperature of the cell is below the calculated dew point temperature.

$$T_d = \frac{b\gamma(T,RH)}{\alpha - \gamma(T,RH)} \tag{1}$$

$$\gamma(T,RH) = \frac{\alpha T}{b+T} + \ln(RH/100) \tag{2}$$

The reference cells were removed from the soiling station after a year of weathering and brought indoors for surface analysis. Microscopy was performed using a Keyence microscope. Extracts of the surface soiling were taken using deionized water (DIW): approximately 5 mL of DIW was pipetted on the surface of each reference cell and soaked for 15 minutes. The DIW was then siphoned off into a glass sample vial. This process was repeated until approximately 40 mL of sample was obtained. The liquid sample was then filtered using nylon membrane filters. Ion chromatography (IC) and total organic carbon (TOC) analysis was then performed on the filtered samples.

B. Glass Coupons

Two uncoated 4 x 6 inch samples of Diamant glass were used for testing. Baseline hemispherical and direct transmittance measurements (Perkin-Elmer Lambda 1050 UV/VIS/NIR Spectrometer) were taken on unaged samples. Samples were then aged outdoors for 11 days (during 10/26/18 – 11/07/18) alongside the measurement station described in Section IIA.

Hemispherical and direct transmittance measurements were then taken on aged samples. Next, the sample surfaces were imaged at 100x on a Keyence VHX microscope. Cleaning at first consisted of only compressed nitrogen air, but no change in surface soiling level was observed. Samples were then rinsed with de-ionized water, dried again with compressed nitrogen, and soiling was reduced. Hemispherical and direct transmittance measurements were taken again, and the samples were re-imaged.

III. Results

During February 2018-2019, 15 soiling intervals have been identified by the soling algorithm [9], with the overall average SRatio measured to be 0.96. The overall SRate for the dataset is -0.22 %/day during soiling intervals. This soiling rate is similar to those observed by Boyle in a similarly classified environment in Colorado in 2015 [11] and 2017 [12].

Microscopy of the reference cells rinsed with DIW revealed heavy soiling on the never-cleaned reference cell and scratches on the brushed reference cell (Fig. 2).

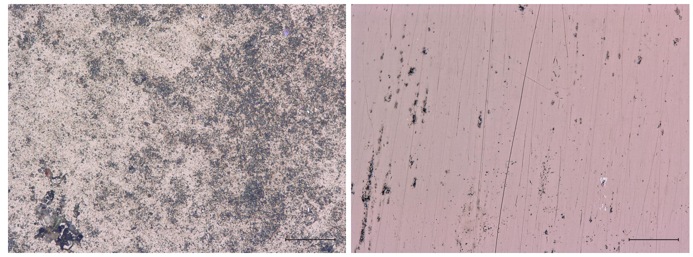

Fig. 2. Left: Micrograph of never-cleaned reference cell aged for 1 year. Right: Micrograph of aged reference cell brushed daily for 1 year. Both samples were rinsed with DIW prior to microscopy. Scale bar (black) represents 100 µm.

Microscopy of the glass coupons aged at the site revealed not only particulate soiling but also circular patterns of soiling likely resulting from the formation and drying of dew droplets on the surface (Fig. 3).

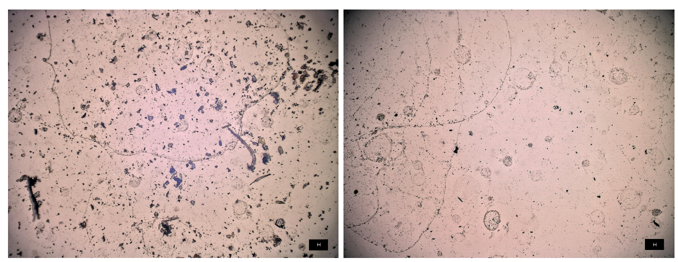

Fig. 3. Left: Micrograph of aged glass coupon. Right: Micrograph of coupon rinsed with DIW then blow-dried. Scale bar (white) represents 25 µm.

During the time that these coupons were aging outdoors, the comparison of the reference cell temp and dew point temperatures confirm that dew formed during this period. The global transmittance drop resulting from soiling was approximately 3-4% for the 11 day period (Fig. 4).

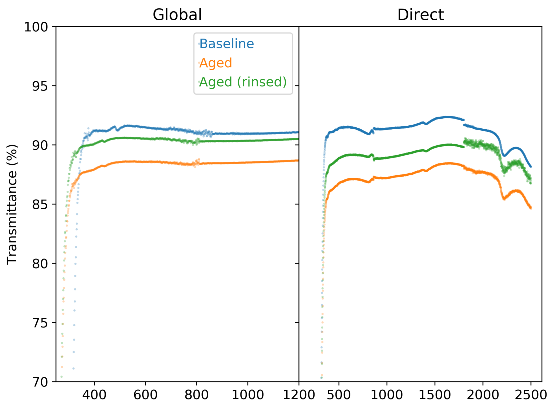

Fig. 4. Left: Global (hemispherical) percent transmittance results for the glass coupon. Right: Direct percent transmittance results for the glass coupon. Note that the rinsing and drying process does not return transmittance levels to baseline, suggesting that natural cleanings are insufficient in this environment.

IC analysis of the DIW-soluble soiling components revealed the most prevalent ion on the two reference cells was chlorine, with nearly equal amounts between the two (Table 1). The "never-cleaned" reference cell refers to the reference cell which was not cleaned for the duration of 1 year outdoors, and the "brushed" reference cell refers to the one that was automatically cleaned daily by the brush on the soiling station. TOC species concentration were also measured.

Table 1.

	Concentration (mg/L)			
Ion	Baseline	Never-cleaned	Brushed	Uncertainty
Cl^-	0.16	77.1	80.5	+/- 0.30
SO_4^{-2}	0.14	4.13	9.98	+/- 0.04
NO_3^-	0.03	0.08	0.21	+/- 0.02
TOC	0.16	8.24	3.91	+/- 0.18

IV. CONCLUSIONS

Using NREL's soiling algorithm [9], 15 soiling intervals were identified during February 2018-2019, with average soiling rate of -0.22 %/day. Conventionally it is assumed that Colorado is a low-soiling location, especially when compared to the desert regions that are home to most large-scale PV systems. However, these results show that urban locations can also soil significantly, which will be an increasing issue as urbanization leads to more power needed in growing cities.

It is possible that the occurrence of dew during the outdoor coupon deployment enhanced the soiling in the subsequent period of time. Soiling intervals were identified during periods with dew formation as well as without dew formation; thus, in this environment dew is not the sole initiating factor of soiling but does play a role in the soiling process.

The transmittance results show that it is unlikely that rain is completely cleaning the surface each time, since the rinsed transmittance levels improve upon the uncleaned levels but do not return to baseline. This is significant to soiling in urban locations since distributed solar systems on residential and small industrial locations are less likely to implement regular maintenance and cleaning practices, and more likely to rely on natural cleaning events such as rain, leading to a buildup of soiling left behind on these systems over time.

The ion chromatography results reveal a chemical residue that builds up on the reference cells and is not removed by dry cleaning, such as the brush mechanism on the soiling station. The presence of chlorine ion could be from a recent application of magnesium chloride ($MgCl_2$) as road-deicer. In urban environments where such chemicals can deposit onto PV, considerations should be made to prioritize wet contact cleaning in order to effectively remove this type of contamination.

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