Renewable Energy 77 (2015) 166–173

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Natural soiling of photovoltaic cover plates and the impact on transmission

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ARTICLE INFO

Article history:
Received 3 March 2014
Accepted 2 December 2014
Available online

Keywords:
Solar energy
Transmission loss
Dust accumulation
Incidence angle

ABSTRACT

Photovoltaic (PV) and other solar energy systems are known to lose efficiency as a result of the accumulation of dust on the surface of the panels. These losses have been difficult to predict and vary widely across geographical regions. In this work dust is allowed to naturally accumulate on PV cover plates at two sites in the Front Range of Colorado. Mass accumulation rates are measured, as well as light transmission reduction. Mass accumulation rates between 1 and 50 mg/m^2/day were observed and varied with time of year, location, and angle of deployment. Total mass accumulations up to 2 g/m^2 were observed after 1–5 week deployments. Transmission reductions up to 11% were found. Transmission varied linearly with the mass of dust accumulated and it was not affected by the angle of incidence of incoming irradiance, angle of deployment of the panel, or location of deployment. Light transmission was found to be reduced by 4.1% for every g/m^2 of dust accumulated on the PV cover plate; this relationship was derived from a linear regression of the data. A linear fit to the data is shown to be sufficient, and the uncertainties of the measurements and calculations are found.

1. Introduction and background

Renewable energy sources are gaining prominence around the globe as energy demand increases, costs of fossil and other non-renewable fuels increase, and issues including climate change and the health effects of poor air quality influence energy production decisions. Renewable energy sources are estimated to have accounted for 16.7% of all energy consumption in 2010 [1]. Solar energy, in particular, is growing at an extraordinary rate with an increase of 75% in the installed photovoltaic (PV) capacity in 2010 (from 40 GW to 70 GW) [1]. The installation of PV is often hindered by economic concerns that are being constantly addressed by increasing panel efficiency and reducing panel cost. However, little research has been done to examine the performance of panels once they have been deployed.

Dust accumulation on the surface of PV and solar heat collector panels as well as Concentrating Solar Power (CSP) mirrors has been reported to create losses of between <1 [2] and 88 [3] percent under ambient conditions. This wide range has been attributed to tilt angle [4,5], location [6], and cleaning factors [5,7]. The first published study of natural dust accumulation on panels found losses of up to 4.2%, but averages of less than 1% for solar heat collectors in Cambridge, Massachusetts [2]. Similar results were found by Nahar and Gupta [4] in India with transmission losses of 1–6% per month for glass samples when tilted from 0° to 90°. However, more recent studies in dustier locations in Egypt found transmission losses up to 25% [8] after one month and 28% [9] after seven months. In Saudi Arabia, Said found a 7% and an 11% loss per month over varying length of tests [10], indicating a significantly larger loss. These studies, while useful in developing an understanding of the problem caused by particle deposition do not help to explain what might happen in locations besides where they were conducted, or present ideas for mitigation strategies; research on the processes involved is needed to take that step.

Those critical processes are (1) airborne particle deposition onto the glazing, and (2) light transmission through deposited particles. Some studies have investigated one or both of these processes in more controlled environments. Using a wind tunnel Goossens and Kerschaever found that increasing the airborne concentration of particulates decreased the power output of a PV cell, and decreasing the wind speed decreased the power output of a PV cell [11]. El-Shobokshy and collaborators deposited varying amounts of sized limestone, cement, and carbon and showed that for the same amount of deposited mass smaller particles decrease the power

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http://dx.doi.org/10.1016/j.renene.2014.12.006
0960-1481/

output from a PV panel more than larger particles [12]. These studies provide useful information about the relationships between airborne particles, environmental parameters, deposited particles, and power loss but real world studies are needed to improve their utility.

A handful of studies have focused on the process of light transmission through deposited particles, with the focus on developing a relationship between deposited mass and light transmission or power loss. Al-Hasan created a theoretical relationship between the mass of particles deposited on the surface and the amount of light transmitted [13], however this relationship requires information on the number and size of particles deposited on the surface, which is rarely known. Mastekvayeva used a curve fit to experimental data to determine the relationship between dust deposition and light transmission, however this was only valid in the heavily deposited range of 5 g/m^2 to 15 g/m^2 [14] which is observed only in the dustiest locations. Elminir and co-workers as well as Hegazy both conducted experiments in Egypt to quantify loss as a function of the amount of dust deposited. Elminir and co-workers developed the relationship:

$$\Delta\tau = 0.0381\omega^4 - 0.8626\omega^3 + 6.4143\omega^2 - 15.051\omega + 16.769 \quad (1)$$

where $\Delta\tau$ is the transmission loss in percent and ω is the dust deposition in g/m^2, by curve fitting data [9]. This relationship was valid between $1.5 < \omega < 9$ g/m^2 which is useful for large deposition values, however deposition values less than 1.5 g/m^2 are common in the Colorado area, and likely many other parts of the world. Hegazy used a similar method to develop a more general equation:

$$\Delta\tau = 34.37\ \mathrm{erf}\left(0.17\omega^{0.8473}\right) \quad (2)$$

which is valid over $0 < \omega < 10$ g/m^2 [8]. While these studies were similar in the location and amount of material that was deposited, they resulted in different relationships, and it is unknown how these equations relate to other locations.

Other parameters in addition to the amount of dust deposited may affect light transmission. The angle of incidence of incoming light could affect the amount of light transmitted through the accumulated dust [13]. The wind speed at which dust deposits effects how much light is transmitted likely caused by ripples being formed when dust deposits at higher wind speeds [11]. The surface or glazing on which the dust accumulates may affect both how the dust accumulates, and light transmission [15]. It has been theorized that the airborne particulate chemistry is important, however has not been demonstrated in the real world [16].

This paper will take a broader process-level approach to the problem of dust accumulation and its resulting impact on light transmission. First, mass accumulation of particles will be examined. Then, the mass accumulation's effect on light transmission will be explored so that the deposition values can be related to solar energy loss. Additionally, uncertainty in all measurements and calculations are analyzed to validate and provide context for the results.

2. Method

2.1. General approach

Glass plates, similar to those used as cover plates for solar energy technologies were exposed to the ambient atmosphere in two locations in the Front Range of Colorado. At each location the plates were deployed at angles of 0°, 40°, and 180° from the horizontal. The plates were covered with a roof that minimized precipitation impacts but still allowed ambient particle deposition. The plates were weighed before and after being deployed to find the mass deposited on the plates, and the transmission of all plates was taken using an ASD Inc. Field Spec Pro 2 spectroradiometer.

2.2. Measurement locations

Two sites in the Colorado Front Range were used for this study. The first was on the roof of a one-story elementary school in Commerce City, Colorado, approximately 10 km northeast of downtown Denver. This site was located in a mixed industrial and residential area with many sources nearby including one major freeway passing 0.6 km to the northwest, and a second major freeway just over 1.5 km to the southwest. Additionally there was a 611 MW coal fired power plant which was being partially decommissioned for conversion to natural gas over the time span of these measurements, and a 98,000 barrel per day oil refinery 3 km to the southwest, as well as an open pit gravel mine less than 0.7 km to the west.

The second site is located at the base of the Boulder Atmospheric Observatory tower in Erie, Colorado. This site is located in a rural area 30 km north of downtown Denver and is surrounded by open fields and farmland. The only other major source is a freeway 2 km to the east. Land use around both sites is shown in Table 1. Fractional land use by class was determined using the 2001 National Land Cover Dataset (NLCD; http://www.mrlc.gov/nlcd2001).

A meteorological monitoring site located between the two sampling locations, which has been in operation for more than 30 years, provided typical meteorological data for the region. The site was 16.8 km south of the Erie site and 10.5 km northwest of the Commerce City site. Average meteorological data for three decades from 1981 to 2010 are given in Table 2 [17]. The monthly average temperatures range from around freezing in winter to 23 °C in the summer. Average total precipitation is 36.4 cm per year, and comes primarily in the spring and summer.

2.3. Description of measurements

2.3.1. Measurement locations

In Commerce City two deposition set-ups were deployed, and in Erie one deposition set-up was deployed. For each of these set-ups,

Table 1
Land use around the sites from the 2001 National Land Cover Dataset.

Site	Land type	Percent in 100 m radius from site	Percent in 1000 m radius from site
Commerce City	Low intensity developed	41	37
	Developed, open space	38	5
	Medium intensity developed	21	34
	High intensity developed	0	11
	Open water	0	9
	Woody wetlands	0	3
	Deciduous forest	0	<1
	Evergreen forest	0	<1
	Emergent herbaceous wetland	0	<1
Erie	Herbaceous	100	14
	Cultivated crops	0	79
	Developed, open space	0	5
	Woody wetlands	0	1
	Developed, low intensity	0	<1
	Barren land	0	<1
	Deciduous forest	0	<1