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Initial Results of a Five Site Study Comparing Spatial Variability of Soiling and Ambient Particulate Concentrations

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***Abstract*—Initial results from a study examining spatial variations of soiling are presented. Soiling from three spatially diverse locations, at US Department of Energy Regional Test Centers, are used: Albuquerque New Mexico, Denver Metro Colorado, and Cocoa Florida. Three separate sites in Colorado that help represent regional diversity are also examined. These locations represent a diverse array of climates in which solar energy may be utilized. Results highlight similarities and differences between soiling at locations across the United States. In addition to soiling data, ambient particulate data is also collected at the five sites, and results from these measurements, and how they relate to soiling, are presented.**

***Index Terms*—Energy efficiency, Solar energy, Soil.**

I. Background and Introduction

Improving models of solar energy forecasts has been a significant research area in the last several years. Improvements in PV performance as well as whole-system performance have improved models and increased confidence in these predictions. Despite these large strides in modeling improvement, there are still several areas that are poorly characterized; one of which is soiling. Soiling of photovoltaic panels can be responsible for large losses in energy production. Previous studies have found both large [1] and small [2] soiling losses, varying with location, climate, and time of year [3]. While some attempts have been made at predicting these losses [3], these attempts have been limited in location and scope, and developing more widespread estimates has proven difficult.

This work aims at providing a greater understanding of soiling variability across the United States. Comparisons are made with ambient particulate matter concentrations, and climate to help make the results generally applicable.

II. Methods

Five different sites were used in this study, three in the area surrounding Denver, Colorado, and two others across broader geographic areas. The sites in Colorado are located on the roof of a one-story elementary school in Commerce City, Colorado, just north of downtown Denver. The second site in Colorado is at the base of the Boulder Atmospheric Observatory Tower in Erie, Colorado, a rural area 20 km north of downtown Denver. The third Colorado site is on the main campus of the National Renewable Energy Laboratory, 15 km west of downtown Denver. The site in New Mexico is in Albuquerque, at Sandia National Labs, home to a Regional Test Center (RTC). The final site is at the University of Central Florida's Florida Solar Energy Center, in Cocoa at a second RTC. A map of the sites is seen in Fig. 1. These five sites provide information about smaller scale differences in soiling in the Denver Metro area, and larger spatial variability of soiling across the United States.

At each of the sites glass coupons, similar to the cover plates used on PV panels, were deployed in two-week intervals to assess the amount of soiling that would occur on PV. At each station, a single coupon was deployed at 40^o, and two coupons were deployed horizontally. As a control one coupon was used as a field blank, brought to the site, put in and immediately removed from the deployment structure. The coupons were mounted in acrylic and wood set-ups that kept the coupons stationary while eliminating edge effects. The samples were also covered with a wood roof to help limit the effects of precipitation. Precipitation has been shown to cause significant cleaning of soiled panels [4] [5], and the aim of this research is not to examine the effects of precipitation. An example of a testing location is seen in Fig. 2. Sample collection began in October 2014 and was continuous at all the sites for six months through April 2015.

Total Suspended Particulates (TSP) were sampled in the same area over the two week period. TSP samples were collected using Hi-Vol TSP filter samplers such as the Tisch environmental TE-5000. These samplers were set to pull 1000 L/min of air through a 8 inch by 10 inch quartz fiber filter that was weighed before and after deployment to estimate the concentration of total suspended particulates in the air. Field blanks were collected bi-monthly to establish the background level of contamination caused by sample preparation, transportation, and handling.

All of the samples (filters and glass coupons) were prepared and weighed at the University of Colorado, and samples were shipped to and from this central location. Pre-deployed plates were cleaned and wrapped in aluminum foil for storage and transport. After being pre-weighed samples were shipped to the New Mexico and Florida locations, or stored on-site until deployment at any of the Colorado locations. After deployment the plates were covered with an identical cleaned glass coupon and wrapped with Teflon tape to prevent deposited particulates from being disturbed. Testing found no appreciable loss in mass from this method. After weighing the glass coupons

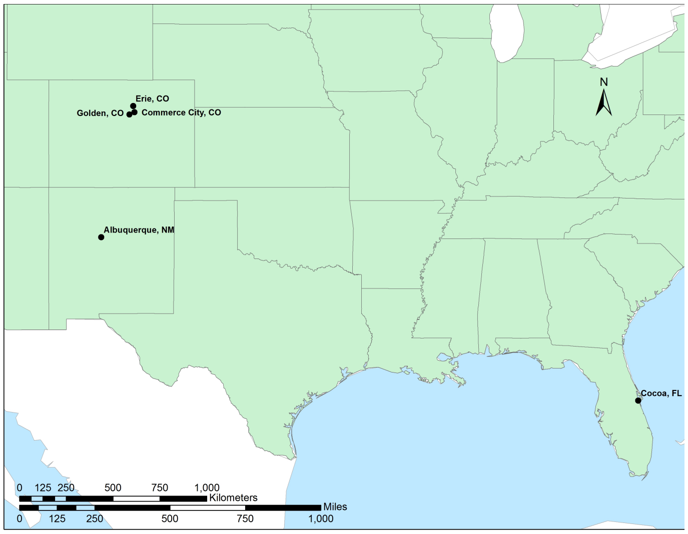

Fig. 1. Map of the site locations used in this study. The sites in Albuquerque, NM and Cocoa, FL are at the sites of Regional Test Centers (RTC). Denver Colorado is home to another RTC, however that site is not used in this study.

Fig. 2. Set-up used for collection of samples in this experiment. On the left is the TSP filter sampler, and on the right is the deposition coupon deployment structure.

they were shipped to Sandia National Laboratories, where transmission measurements were taken. Transmission measurements were collected with a Varian Cary 5000 UV/vis/NIR spectrophotometer. Pre-deployed TSP filters were baked at 500°C for 12 hours in aluminum foil sleeves to clean the filters before being pre-weighed. After deployment the TSP filters were returned to their Aluminum sleeves for transport and storage.

Glass coupons and TSP filters were weighed before and after being deployed. Samples were equilibrated in a temperature and relative humidity controlled chamber for at least 24 hours before being weighed on a Satorius scale with a 0.00001g accuracy. The difference of the pre and post weights was taken as the mass of deposited particles for the glass coupons, and the mass of particulates in the volume of air passed through the filter (1000 L/min times the number of minutes deployed) for the TSP filters.

III. Discussions and Conclusions

A. *Mass Accumulation*

Mass accumulation rates from 0 to 0.05 g/m^2/day were observed in this study. Mass accumulation rates were similar at all the sites except the Erie site where they were on average significantly lower. These mass accumulation rates are similar to rates seen in other work [6]. There may be some reasonably acceptable estimates for estimating mass accumulation for soiling rates throughout the continental United States because of the similarity in deposition rates between four of the five sites. These rates are similar despite widely varying climates, local topography, and surrounding environments. However the significantly different mass accumulation rates observed at the Erie site, despite being relatively close (within 40km) of two other sites indicates that local conditions can not be ignored when estimating soiling losses.

One possible explination for lower mass accumulation rates at the Erie site is lower airborne particulate concentrations [7] [8]. For this reason ambient particulate concentrations were monitored at each field location and compared to the mass accumulation.

B. *Particulate Concentrations*

TSP concentrations ranged from 0 to 35 μg/m^3. Low TSP concentrations are primarily caused by precipitation, and higher particulate concentrations are often caused by the accumulation of particulates in the atmosphere, generally from local sources. A plot of simultaneously collected ambient particulates (TSP) and mass accumulation is shown in Fig. 3. This shows no clear relationship between TSP and mass accumulation in general or for any of the sites individually. More data is needed to make conclusions about if the relationship between mass accumulation and TSP is site dependent, and if so what parameters at each site might determine this. Wind speed, humidity, and make-up of ambient particulates could also be driving forces in deposition [9] [10].

Fig. 3 indicates that ambient particulate concentrations are not a driving factor in predicting soiling in general. However it is believed that high uncertainty in the TSP concentration measurements could be obscuring trends between ambient particulates and mass accumulation.

C. *Trasmission*

Previous studies have shown a clear relationship between total mass accumulated and transmission loss [11] [12], but no study has shown that this relationship is independent of location. Fig. 4 shows the relationship between mass accumulated and transmission loss for all the samples, color coordinated for location of deployment. A clear trend is seen in this data. The linear fit to the data gives:

$$\Delta\tau = 5.5 * m_{accumulated} \tag{1}$$

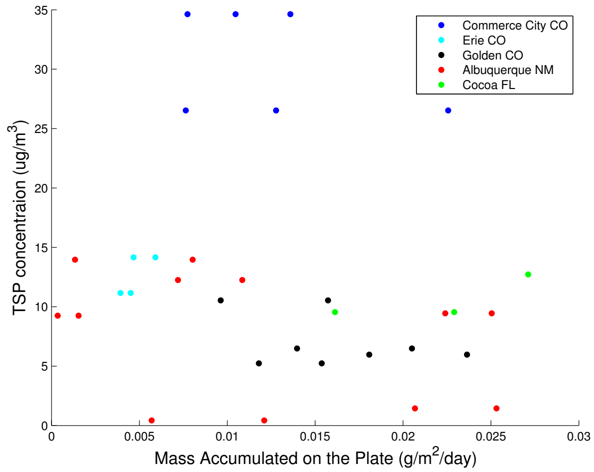

Fig. 3. Comparison of ambient particulate concentrations and mass accumulation on PV cover plates at the five sites used in this study. A lack of a clear relationship is an indication that soiling may be heavily site dependent, with respect to ambient concentrations. More data is needed to see how well soiling at each site may be predicted by ambient particulate concentration measurements

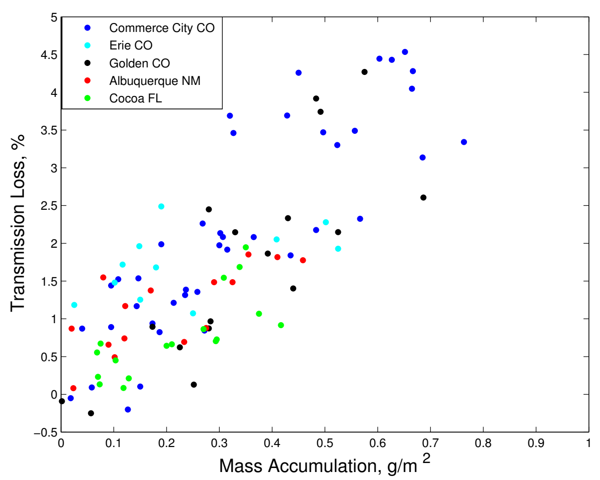

Fig. 4. Comparison of mass accumulation on PV cover plate and transmission loss at the five sites used in this study. There is a clear relationship between mass accumulation and transmission loss that is not location dependent.

where $\Delta\tau$ is the transmission loss (or change in transmission), and $m_{accumulated}$ is the mass accumulation. That is for every g/m^2 of mass accumulated on the surface of a PV panel a 5.5% loss in transmission is observed. It is important to note that this data set only includes samples soiled up to 0.8 g/m^2. These data do not show a location dependence for the relationship in Eq. 1 for these five sites. This is a strong indication that this relationship, can be used at any site in the continental United States, and perhaps anywhere in the world.

These results can help inform modeling of solar energy forecasting. While this work does not show any clear path for modeling mass accumulation, it does show location independence for the relationship between mass accumulation and transmission loss.

IV. Acknowledgements

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