Science of the Total Environment 651 (2019) 456–465

Contents lists available at ScienceDirect

Science of the Total Environment

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

The impact of air pollutant deposition on solar energy system efficiency: An approach to estimate PV soiling effects with the Community Multiscale Air Quality (CMAQ) model

Luxi Zhou [a,b,*], Donna B. Schwede [a], K. Wyat Appel [a], Michael J. Mangiante [a,1], David C. Wong [a], Sergey L. Napelenok [a], Pai-Yei Whung [a], Banglin Zhang [c]

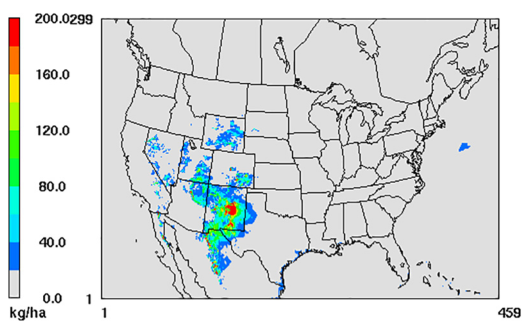
[a] U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, United States
[b] National Academies of Science, Engineering and Medicine, Washington, DC 20001, United States
[c] Institute of Tropical and Marine Meteorology/Guangdong Provincial Key Laboratory of Regional Numerical Weather Prediction, CMA, Guangzhou 510641, China

HIGHLIGHTS

- CMAQ model overestimates $PM_{2.5}$ concentration but underestimates PM_{10} concentrations at selected three sites in U.S.
- CMAQ model underestimates PM_{10} deposition at three sites.
- PV panel transmittance losses estimated based on the modeled particle deposition are lower compared to on-site measurements.
- The transmittance loss estimates are comparable to other observations in U.S., indicating applicability of the approach.

GRAPHICAL ABSTRACT

Average PM_{10} accumulation in April 2011



ARTICLE INFO

Article history:
Received 11 June 2018
Received in revised form 11 September 2018
Accepted 15 September 2018
Available online 17 September 2018

Editor: Jay Gan

Keywords:
Air quality
Deposition
Soiling effect
Solar PV
Air quality modeling

ABSTRACT

Deposition and accumulation of aerosol particles on photovoltaics (PV) panels, which is commonly referred to as "soiling of PV panels," impacts the performance of the PV energy system. It is desirable to estimate the soiling effect at different locations and times for modeling the PV system performance and devising cost-effective mitigation. This study presents an approach to estimate the soiling effect by utilizing particulate matter (PM) dry deposition estimates from air quality model simulations. The Community Multiscale Air Quality (CMAQ) modeling system used in this study was developed by the U.S. Environmental Protection Agency (U.S. EPA) for air quality assessments, rule-making, and research. Three deposition estimates based on different surface roughness length parameters assumed in CMAQ were used to illustrate the soling effect in different land-use types. The results were analyzed for three locations in the U.S. for year 2011. One urban and one suburban location in Colorado were selected because there have been field measurements of particle deposition on solar panels and analysis on the consequent soiling effect performed at these locations. The third location is a coastal city in Texas, the City of Brownsville. These three locations have distinct ambient environments. CMAQ underestimates particle deposition by 40% to 80% when compared to the field measurements at the two sites in Colorado due to the underestimations in both the ambient PM_{10} concentration and deposition velocity. The estimated panel transmittance sensitivity due to the deposited particles is higher than the sensitivity obtained from the measurements in

* Corresponding author at: U.S. Environmental Protection Agency, Research Triangle Park, NC 27711, United States.
E-mail address: zhou.luxi@epa.gov (L. Zhou).

[1] Now at Environmental Resource Management, Washington, DC 20006.

https://doi.org/10.1016/j.scitotenv.2018.09.194

Colorado. The final soiling effect, which is transmittance loss, is estimated as 3.17 ± 4.20% for the Texas site, 0.45 ± 0.33%, and 0.31 ± 0.25% for the Colorado sites. Although the numbers are lower compared to the measurements in Colorado, the results are comparable with the soiling effects observed in U.S.

1. Introduction

1.1. The soiling of photovoltaic panels

Soiling of photovoltaic (PV) panels, which is the process by which airborne particles deposit and accumulate on solar panels, impacts the performance of the PV energy system. The deposited particles on the panel absorb and backscatter part of the incident solar radiation, thereby reducing the panel energy transmittance. The performance loss due to the soiling of panels, referred to as the soiling effect, varies by environment. In sunny, arid, dusty regions such as the Middle East and India, the power losses have been reported to be between 20% to 70% (Elminir et al., 2006; Hasan and Sayigh, 1992; Hegazy, 2001; Said, 1990; Sayigh et al., 1985), while in locations with frequent precipitation or low ambient particle concentration, the energy loss is typically below 5% (Hottel and Woertz, 1942; Sarver et al., 2013). A recent study reports a 2.8% reduction in energy transmittance for every g/m^2 of particulate matter deposited on the solar panel based on observations from five locations across the continental U.S. (Boyle et al., 2017). In addition to spatial variation, the performance loss can vary when deposited particles on the panel accumulate over time and then get removed by wind, precipitation, or other manual cleaning mechanisms and changes according to system's specifications, such as panel material, tilt angle (Sarver et al., 2013; Maghami et al., 2016; Ahmed et al., 2013).

It is desirable to determine the expected soiling effect at a given location because the effect decreases the system energy production by decreasing the solar panel transmittance while also increasing the uncertainty in system performance. The National Renewable Energy Laboratory (NREL) has generated a map that highlights soiling effect information from parameters of fielded PV panels at >80 locations across the U.S where there is ongoing soiling measurements or past measurements (National Renewable Research Laboratory). However, because soiling rate varies across time due to changes in the environment, a map showing soiling rate base on past or on-going measurements may not serve well the need in predicting soiling effect. Past modeling efforts include prognostics models that predict the soiling effect based on physical parameters such as wind speed, temperature, and radiation (Chokor et al., 2016). The suitability of these models is unfortunately often limited to a specific location. Other attempts include more advanced data sciences. For example, an artificial neural network (ANN) approach was applied to model PV panel cleanliness in a field at Doha Qatar (Javed et al., 2017). Although the ANN model is theoretically applicable to any place, it is still constrained by the availability of high quality measurement data in practice. There are multiple factors impacting the soiling effect, such as site-specific environment (e.g., significant emission sources and wind erosion), meteorological parameters, and the PV system specifications. Micheli and Muller (2017) quantified the strength of the correlation between the soiling effects and 102 environmental or meteorological parameters across 20 sites located in eight states of the U.S. In addition to meteorological parameters (such as precipitation frequency, accumulated precipitation, and wind speed), air pollution data (such as mean PM2.5 and PM10 concentrations within certain distances of the site), site environment specification parameters (such as distance from a highway, distance from dirt roads, distance from the ocean, and the wind erosion index), hazard related parameters (such as fire risk regime), panel characteristics (e.g., tilt angel, angle between wind direction, and panel surface) and land use related parameters. The results showed that the annual average of daily mean particulate matter (PM) concentration recorded by monitoring stations deployed near the PV systems is the best predictor of soiling effect, implying that ambient air quality has a significant impact on solar panel efficiency. In addition, among different meteorological parameters precipitation pattern was also found to be the most relevant because the average length of dry periods had the best correlation with the soiling ratio.

Despite numerous studies on the soiling issue by the solar energy research community in past decades, a comprehensive review by the National Renewable Energy Laboratory (NREL) pointed out that the fundamental processes related to particle deposition and their effect on energy transfer are still not fully understood (Sarver et al., 2013). The purpose of this study is to design and examine an approach to estimate the soiling effect by utilizing PM dry deposition estimations from air quality model simulations and available optical properties. The Community Multiscale Air Quality Modeling System (CMAQ) used in this study is a state-of-the-art air quality model that undergoes continuous development and updating by the U.S. Environmental Protection Agency (U.S. EPA) and is routinely used for air quality forecasts, regulation, and research purposes (U.S. EPA. Office of Research and Development, 2017; Byun and Schere, 2006). The results from the analysis are evaluated at three continental U.S. locations. These locations include an urban site, Commerce City, Colorado (CC); a suburban site, Erie, Colorado (ER); and a coastal city site, Brownsville, Texas (BV). The sites in Colorado (sites CC and ER) were selected because there have been past studies that conducted field measurements of particle deposition on solar panels and analysis of the consequent soiling effect at these locations (Boyle et al., 2014, 2015), while the site in Texas (site BV) was chosen since the soiling effect estimated for BV in this study would be incorporated into an energy economic assessment project for the city. As a port city, BV is different from CC and ER in terms of weather and emission sources of particles, providing a case to test the proposed approach in a different environment. While there are multiple factors impacting the particle deposition estimates, we focus on the impact of land-use type by analyzing three sets of simulations based on different surface roughness length, which is the sole relevant land-use type parameter for particle deposition simulation. The evaluation conducted for the three sites with three different roughness length assumptions will provide a synthesis on how the choice of land-use type could impact atmosphere-surface particle exchange in general and how the presented approach could be applied to estimate soiling effects in practice.

2. Methods

2.1. Description of the particle dry deposition process in CMAQ model

The Community Multiscale Air Quality (CMAQ) Model is a computational tool for both air quality management and atmospheric research (U.S. EPA. Office of Research and Development, 2017; Byun and Schere, 2006). The model represents atmospheric processes including emissions from anthropogenic and biogenic sources, meteorological transport, atmospheric chemical reactions, radiation, cloud processing, and deposition. Dry deposition is the exchange process of pollutants from the Earth's atmosphere to its surface in the absence of precipitation (Pryor et al., 2008; Petroff et al., 2008). The parameterizations of dry deposition velocity in the CMAQ model are represented by electrical resistance analogs. In case of aerosols, the resistances consist of aerodynamic resistance R_a and quasi-laminar boundary layer resistance R_b (Pleim and Ran, 2011).