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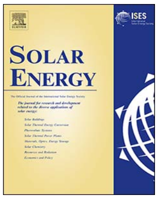

Effects of atmospheric dust deposition on solar PV energy production in a desert environment

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ABSTRACT

The effect of deposition of atmospheric dust onto photovoltaic modules is investigated using both field measurements and modeling. Energy yield, solar irradiance, ambient particulate matter concentrations, and meteorological data were monitored during a 12-month period at a solar test facility in the arid environment of Qatar. Dust concentration alone, is a weak predictor of PV soiling and performance, even for particles larger than 10 µm. Instead, a non-linear correlation between aerosol mass, RH and PV losses was observed. A dynamically resolved three-dimensional aerosol dispersion model coupled with online meteorology was employed to simulate the emissions and transport of dust particles in the surrounding environment. The advantage of using such a model is that most of the complexities of the deposition process are grouped together in a single parameter: the particle deposition velocity. The model predicts an average deposition velocity ranging between 1.1 cm s^{-1} and 3.3 cm s^{-1} during summer and 1.6 cm s^{-1} and 3.7 cm s^{-1} in winter for the different size ranges of coarse dust particles. A numerical weather prediction model coupled with an explicit treatment of aerosols could be a beneficial tool for comprehensive PV soiling predictive capabilities on an urban-to-regional scale. Results from the predicted geographical distribution of dust settling suggests that floating PV modules could benefit from significantly lower dust deposition.

1. Introduction

Solar energy production is growing rapidly worldwide. Research on photovoltaic (PV) systems has traditionally focused on the intensity of solar irradiance, PV panel surface material, tilt angle of the absorbing surface, and temperature losses. In arid environments, building large PV projects is particularly appealing due to significantly enhanced solar exposure and availability of vacant land. However, PV soiling is a major concern in desert climates: Accumulation of dust particles on the surface of PV modules is currently a major contributing factor in the reduction of overall PV performance, especially in dry regions such as the Middle East (Levitan, 2013; Sarver et al., 2013).

Energy losses due to soiling exhibit large variations depending on the location, meteorology (wind speed, wind direction and humidity) and various atmospheric parameters (such as ambient particulate matter (PM) concentration, particle size and chemical composition, aerosol gravitational settling, and solar irradiance). Among the most important of these parameters seem to be the wind speed, the gravitational forces and the particle size/mass (Micheli and Muller, 2017; Mani and Pillai, 2010; Goosens and Kerschaever, 1999). PV soiling is usually measured by determining the accumulated particle mass or the light transmittance loss on small collection coupons. Another method is the measurement of the energy yield loss or the short-circuit current of PV modules.

Hegazy (2001) found a relationship between the mass of deposited PM and the loss in solar energy due to reduced transmittance, regardless of the tilt angle. This correlation was valid under certain conditions of particle mass density and thus not easily generalized to other environments. Elminir et al. (2006) measured the reduction in transmittance on 100 glass coupon samples over a period of seven months and found strong dependence on the dust deposition density estimating a PV output power reduction up to 80% depending on the plate tilt angle and the orientation of the surface. Beattie et al. (2012) described the process of particle accumulation on PV by an exponential decay for dry regions while estimating a wind speed threshold above which particles are removed from the surface. They also identified atmospheric moisture/humidity as an important factor that strongly influences particle accumulation/removal and should be the focus of future investigations. More recently, the effect of dust on PV panels was investigated in Kuwait during a period of two corresponding months (May of 2010 and

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2011) by measuring spectral transmittance for different PV technologies and tilt angles and for varying air masses (Qasem et al., 2014). A relation was found between spectral transmittance and dust density for low amounts of deposited dust ($< 19\,\mathrm{mg/cm^2}$).

Although research so far has shown a clear relationship between the measured PM deposition on solar PV modules and their energy output, predicting these output losses is still in its infancy (Beattie et al., 2012; Boyle et al., 2016); difficulties in predictions are attributed to the complicated effect of environmental and weather parameters such as humidity, wind speed, particle mass and possibly other unexplored parameters. Micheli and Muller (2017) conducted a comprehensive analysis of more than a hundred environmental parameters combined with data from 20 soiling stations in the US and showed that particulate matter data from monitoring stations combined with a classification of humid/dry conditions is the best soiling predictor. In the PM-rich desert environment of the Middle East, Guo et al. (2015) determined the soiling rate of an eight-module PV system in Qatar by measuring the daily decrease in energy yield. They found no clear correlation between the soiling rate and the measured ambient PM_{10} (PM with a diameter of less than 10 μm), the relative humidity (RH), or the wind speed. With the aim to achieve stronger correlations by increasing the time-resolution of the measurements, Figgis et al. (2016) developed an outdoor soiling microscope measuring deposition and removal of particles every 10 min in real time. Although some qualitative relations were found which were not seen in the daily data (Guo et al., 2015), correlation coefficients remained surprisingly low suggesting the need for a more sophisticated soiling model including a greater number of variables.

Interestingly, although the measured deposited PM mass correlates well with the energy loss data, the observed ambient PM was only weakly correlated in those studies (Guo et al., 2015; Figsgis et al., 2016). In this work, we apply an atmospheric pollution dispersion model that predicts PM concentration along with a set of atmospheric parameters, in an effort to correlate model-predicted PM characteristics (some of which cannot be measured) with the PV energy loss data from a solar test facility in Doha, Qatar. The goal of this work is to provide a foundation for the development of a comprehensive soiling predictive tool, which so far does not exist.

2. Material and methods

2.1. Measurements of ambient PM concentration and PV energy loss

PV energy production data was collected for a period of one year (1 May 2015 – 1 May 2016) at the Solar Test Facility (STF), located at the Qatar Science & Technology Park in Doha, Qatar (operated by the Qatar Environment and Energy Research Institute). The PV arrays that were used in this study are polysilicon modules tilted at 22° facing south. The measured daily energy yield was temperature-corrected and normalized with the measured plane of solar radiation, giving units of kW h/day/kW_p. Ambient PM_{10} and $PM_{2.5}$ concentration were measured continuously (every hour) during the same 12-month period in the air quality monitoring station located in the STF (immediately next to the PV modules) by a PM analyzer (MP101 M) suited with an impact plate sampling head (USEPA PM10) which measured the absorption of radiation of a sample of mass when exposed to a Beta radiation source as a function of the mass of the irradiated material. Additionally, the air monitoring station was equipped with a Thermo-hygrometer (DMA867-875) for continuous measurements (every 1 min) of ambient relative humidity and temperature as well as an Anemometer (DNA827) for the wind velocity and wind direction.

2.2. Atmospheric dust modeling

Generating accurate predictions of the spatial and temporal variation of particle concentrations in a system as complex as the atmosphere -involving numerous physical and chemical processes that occur simultaneously- requires the use of a numerical chemical transport model. Within this work the three dimensional meteorology-chemistry model WRF-Chem (Weather Research Forecasting with Chemistry [Fast et al., 2006; Grell et al., 2005]) was employed over the Arabian Peninsula region with an enhanced grid resolution over the state of Qatar (Fountoukis et al., 2016). The WRF-Chem model simulated the three basic components: emissions of atmospheric constituents (gases and aerosol particles); transport of constituents; and the physicochemical transformations of atmospheric species. The model was applied over the Middle Eastern Area in a domain of 3-D grids on a two-way nesting configuration in which three domains at different grid resolutions communicate with each other and are run simultaneously (Fig. 1). Information concerning dust concentrations propagates into and out of all computational domains during the model integration. The parent domain used a 50 km × 50 km grid resolution while the intermediate nested domain (focused on the Arabian Desert) used a 10 km × 10 km resolution. The third domain was configured over the region of Qatar and was resolved at 2 km × 2 km. This grid nesting capability of WRF-Chem allows for a computationally efficient model capable of spanning large areas in which regional transport of dust is important, while providing fine resolution in select areas to address small-scale features. The altitude coordinate was discretized into 28 vertical layers in all three computational domains, extending from the surface to approximately 20 km. The simulation runs model two periods of 30 days each, representative of a typical summer (1–31 July 2015) and winter (19 Jan – 18 Feb 2016) time in Qatar. Each simulation run was initialized and permitted to simulate for 10 days in advance to the model period; this span of time is considered a spin-up time and was excluded from the analysis to limit any extraneous negative effects due to the initial conditions. WRF-Chem was set to perform all simulation runs on a lambert map projection.

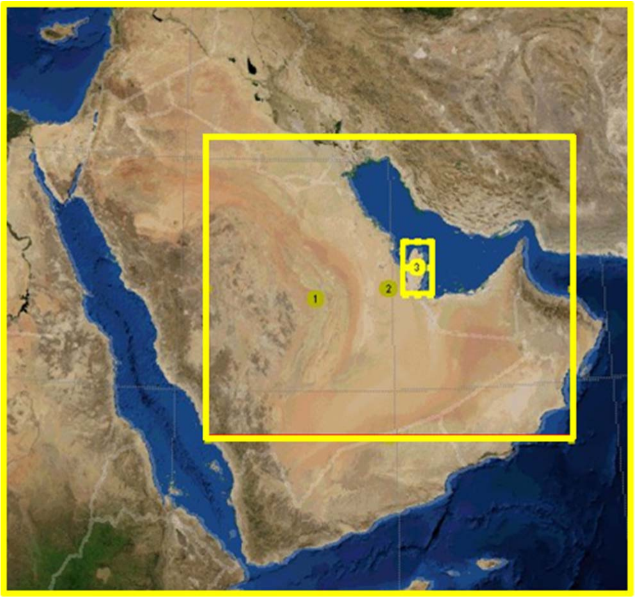

Fig. 1. Modeling domains at (1): 50 km × 50 km, (2): 10 km × 10 km and (3): 2 km × 2 km over the Arabian Peninsula. The numbers 1, 2 and 3 indicate the center point of each of the three computational domains, respectively.

The GOCART (Georgia Institute of Technology–Goddard Global Ozone Chemistry Aerosol Radiation and Transport) aerosol scheme (Ginoux et al., 2001; Kok, 2011) was used in all simulations along with the RACM (Regional Atmospheric Chemistry Mechanism) chemistry scheme (Stockwell et al., 1997; Geiger et al., 2003). The HTAP (Hemispheric Transport of Air Pollution emissions; http://www.htap.org/) anthropogenic emissions were used with a grid resolution of 0.1° × 0.1° and include: non-methane volatile organic compounds (NMVOCs), nitrogen oxides (NO_x), ammonia (NH_3), carbon monoxide