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The effect of dust on solar photovoltaic systems

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Abstract

Soiling is the accumulation of dust on solar panels that causes a decrease in optical efficiencies of CSP systems. However, geographically widespread data is only available for solar photovoltaic (PV) systems. The changes in efficiency of a large commercial site (86.4 kW_{dc}) was quantified during the summer dry period over the course of 2010 with respect to rain events observed at a nearby weather station (3.4 km away) and using satellite solar resource data. Soiling losses were found to be 0.21% per day. The site was observed to have a decrease in efficiency from 7.2% to 5.6% during a 108 day dry period in the summer at which point a rain event occurred that recovered most of the lost efficiency going back to 7.1%.

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1. Introduction

Concentrated solar power (CSP) power is quickly increasing in California with the Ivanpah power tower facilities and several concentrating photovoltaic (CPV) power plants in the Imperial Valley. Soiling significantly impacts the optical efficiency of CSP systems, but geographically dispersed, robust estimates on soiling have been elusive. The California Solar Initiative now provides photovoltaic (PV) performance data from which soiling estimates can be derived. Even for PV, soiling can be significant and influence the management and analysis of the expected performance of PV sites.

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Fig.1 demonstrates how dust has accumulated on a PV panel. Dust accumulation can have a large effect on efficiency during long droughts [1], which unfortunately is also when the largest solar resource occurs.

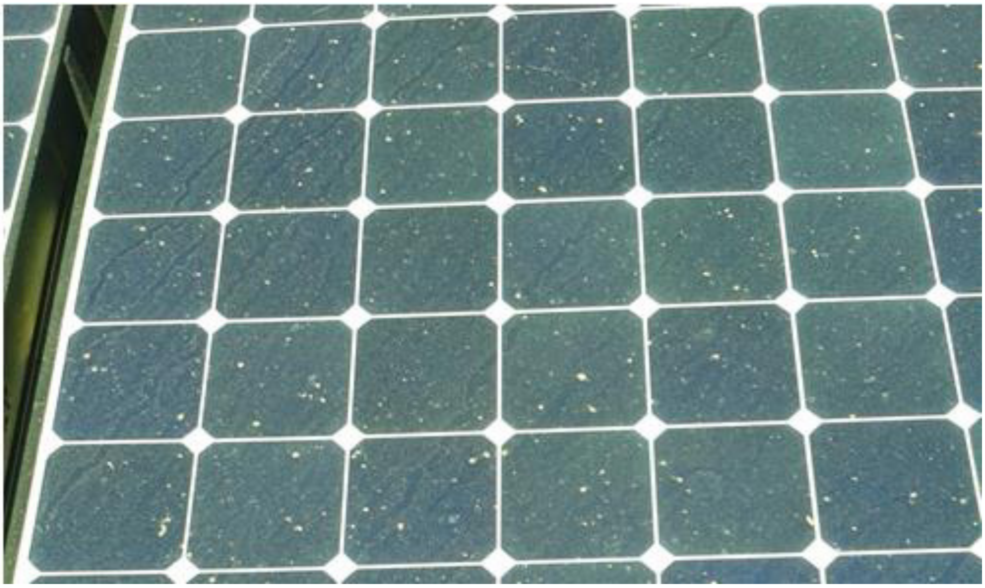

Fig. 1 Dust accumulation on PV panel in UCSD.

Some research on soiling has been conducted particularly in the middle-east [2, 3] and India [4]. Another more recent study examined the effects of soiling for 250 sites monitored by PowerLight (now SunPower) [1]. Since several of these sites are in areas with frequent rain their study focused on sites in the southwestern United States where long droughts are more common. They also excluded sites with an R^2 value between soiling energy losses and time of less than 0.7 which left a total of 46 sites. Between rain events, soiling losses were found to aggregate linearly with time with an average daily soiling loss of 0.2%. While this paper provides a methodological foundation for analysing soiling losses, the site selection criteria may have led to an overestimate of soiling losses [11].

A few studies have been conducted attempting to connect the effects of soiling in flat PV with those of CPV and have shown that CPV has greater losses due to soiling than flat PV. The main difference between these systems is that in CPV using an optical system to focus sunlight onto a smaller area either with reflectors or Fresnel lenses. For mirrors soiling can affect the system both when it enters the mirror and when it exits the mirror leading to greater losses [12]. Beyond this, CPV rely on keeping radiation reflected within a certain angle so that it can reach the solar cell. Small deviations in the trajectory of the radiation that did not affect flat panel PV, may lead the radiation away from the solar cell. One paper found a link between flat PV and CPV by comparing 5 concentrating systems of varying concentrating levels from 2X to 300X with a flat panel for 4 months [13]. They found a relationship between the concentration level and the losses observed do to soiling and also found that reflective systems were more susceptible to soiling losses than refractive systems.

2. Data

2.1. Photovoltaic site and rain data

The Performance Based Incentive (PBI) program of the California Solar Initiative (CSI) rebate program requires accurate energy output metering [5]. AC energy generation has to be collected every 15 minutes and submitted monthly. The AC power produced from a large commercial site (86.4 kW_{dc}) in Santa Clara, California was obtained for the year of 2010. One of the reasons this site was selected is because of its close location to a weather station that provides accurate data that is used for this analysis. The other reason is that this site exhibited typical trends observed in sites where soiling occurs, such as a linear decay during dry periods and sharp increase in performance after a rain event.

Data from the California Irrigation Management Information Systems (CIMIS) was used to estimate the amount of rain at each CSI site. Hourly data from a CIMIS station 3.4 km away from the PV site was obtained and verified with other nearby stations to quality control the data. Fig.2 demonstrates the location of the PV site and the CIMIS station that was used.

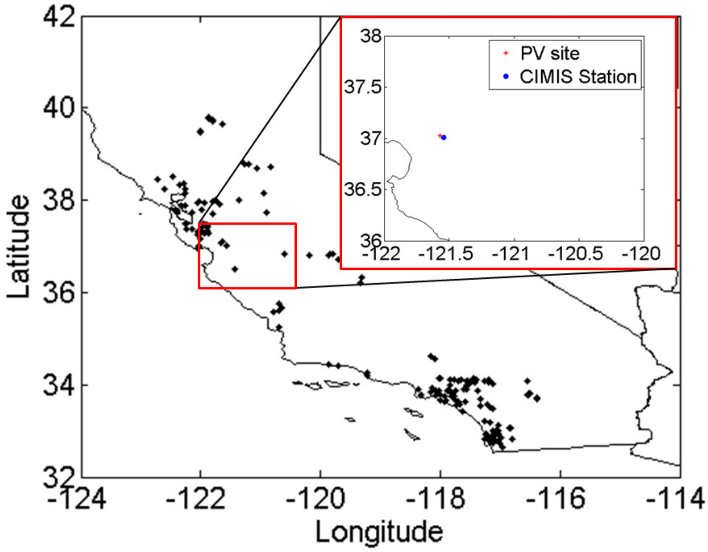

Fig. 2 Location of PV site and CIMIS station.

2.2 Solar conversion efficiency

The 15 minute data from the site was averaged to eliminate the daily variations of the data and provide a more accurate estimate of the PV efficiency. The estimated solar irradiation from SolarAnywhere (SAW) was used to model the solar resource at the site. SAW uses satellite images to derive global horizontal (GHI) and direct normal irradiation (DNI) every 30 minutes at 1 km resolution. SAW's solar irradiation shows a typical mean bias error of 3% for GHI and no persistent error trends across the year [6]. Using the average daily energy produced from the CSI site (P_{CSI}) and the average daily incident solar energy modeled from SAW (P_{SAW}), the daily DC solar conversion efficiency (η) for the solar panels was calculated, controlling for the effects of temperature η_T and inverter η_{AC} efficiency as follows:

$$\eta = \frac{P_{CSI}}{P_{SAW}} \quad (1)$$

$$P_{SAW} = \frac{GI_{SAW}}{1000\ \mathrm{W\ m^2}} P_{rated}\eta_{AC}\eta_T \ (2),$$

where GI_{SAW} is SolarAnywhere global irradiation at the plane-of-array transposed using the Page model [7] and P_{rated} is the rated DC power output of the site. PV cell temperature and temperature efficiency correction were modeled as in [8] and $\eta_T = 1 - \alpha(T_{cell} - 25^o\mathrm{C})$ with $\alpha = 0.5$ % C^{-1}, respectively, using the actual temperature of the PV cell. Inverter efficiency was modeled using a 3rd order polynomial versus power factor as in [9].

2.3 Rain events

The amount of dust that is present in a PV panel is a balance between how much dust is collecting on the panel and how much is being removed. The main ways that dust can be removed is by scheduled cleaning, wind or rain. This was analysed by averaging η for the week before a rain event (η_b) and for the week after a rain event (η_a). The difference ($\eta_a - \eta_b$) was then assumed to be the increase in efficiency that is caused by a rain event. However, no correlation between rain amount and change in efficiency was observed consistent with [1], probably because the majority of soiling durations are only 10s of days and during such a short time soiling losses are smaller than other sources of variations in efficiency. The only drought long enough for soiling to outweigh other sources variations was during the summer so this is the region of the year that will be the focus of this study.

2.4 Quantifying losses due to soiling

As demonstrated in Fig. 3a, a strong decrease in efficiency is observed during the summer drought. At the site, there is a steady decrease in the efficiency of the PV plant after the last rainfall before summer (day 142). Fig. 2b demonstrates how the degradation follows a linear trend that is consistent with literature [1, 11]. It is also clear that the slight rain events (< 0.02 in) during the summer are unable to clean the panel and it is not until the rain events in the fall restore the PV plant to the efficiency observed at the beginning of the year. Note that the large day-to-day variability in solar conversion efficiency is caused by random errors in the satellite solar resource model that average out when longer periods are considered. A weekly moving average was used for Fig. 3 to better demonstrate the long period trends.

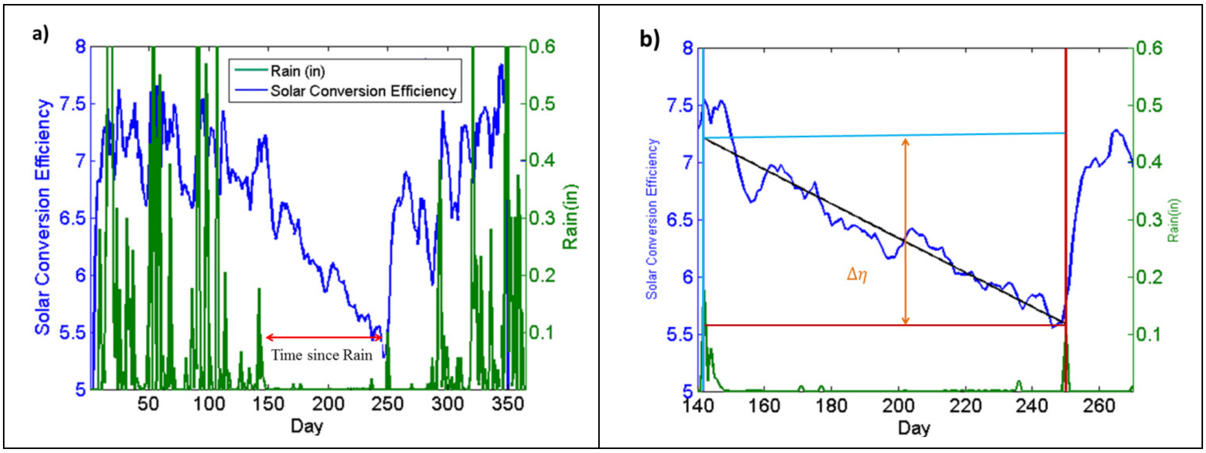

Fig. 3a) Timeseries of daily solar conversion efficiency η and daily rainfall for a 86.4 $\mathrm{kW_{dc}}$ PV plant in Santa Clara, CA in 2010 b) Linear regression of efficiency versus days since last rain in black. $\Delta\eta$ is expressed as the first (blue) minus the last (red) value of the drought period.

Fig. 3b demonstrates the calculations used to identify the soiling losses for this site. A best fit line is fitted through the data during the summer drought season. The slope of the best fit line is then assumed to be the daily soiling for that drought. The calculations can be observed in Fig. 3b, where the soiling losses for that drought period were found to be -0.0021 day^{-1}. In other words, this site begins with an efficiency of 7.2% and after 108 days it loses a factor of 0.22 or 22% of its original efficiency leaving it with 5.6%

This method was previously shown to quantify soiling [1, 11]. The main assumption of this method is that the efficiency changes are caused by soiling and not by other factors such as panel degradation and seasonal errors in the SAW resource model. In general, these other factors are small or should average out over many sites and rain events. Another assumption in this method is that the panel has the same amount of dust at both the beginning of the drought season (day 142) as it does at the end of the drought period (day 250).

3. Results and discussion

As demonstrated in the previous section a large amount of soiling was observed during the summer drought. This site had yearly average efficiency of 6.8% and the daily soiling losses were found to be -0.0021/day. During the summer drought the site lost 1.6 % efficiency as seen in fig. 3 the efficiency of the site goes down from 7.2% to 5.6%. The efficiency of the site has a large jump during the first major rain event in the fall suggesting that the losses were in fact caused by soiling.

How much additional solar energy could be harvested through panel washing? Manual washing is expensive and typically only scheduled during the summer drought. We estimate impacts of one annual washing based on the soiling losses and the one half the length of the summer drought for each site. This estimate is assuming that normal soiling is observed and halfway through the summer an automated washing system thoroughly cleans the panel and returns is efficiency to that observed during the spring. After this cleaning the panel continues loosing performance due to soiling until it is naturally clean by rain. This process is demonstrated in fig. 4.The site would have yielded 1.75% more annual energy if it had been washed halfway through the summer drought period.

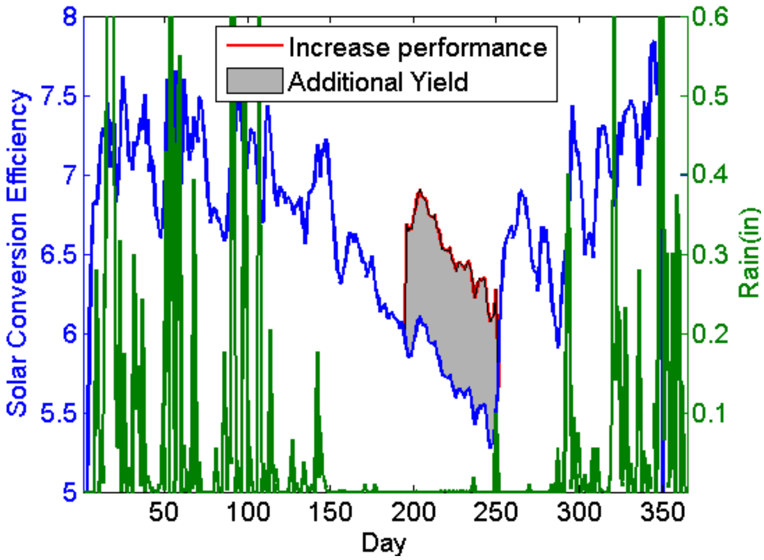

Fig 4. Increase performance due to cleaning panel halfway through the summer plotted in red. Increased additional energy harvested plotted in gray.

If an automated cleaning system was installed to clean the sites regularly, larger energy gains would be possible, on average 11.1% of annual energy. This estimate is calculated by assuming that the annual maximum of the 30 day moving average efficiency equals the energy output for a completely clean panel. The extra yield (Fig. 5) is then calculated as the integral between the efficiency of this clean panel and the actual observed efficiency. Fig.5 demonstrates the 30 day moving average efficiency in blue and in red the ideal efficiency that could be observed with an automated daily cleaning system.

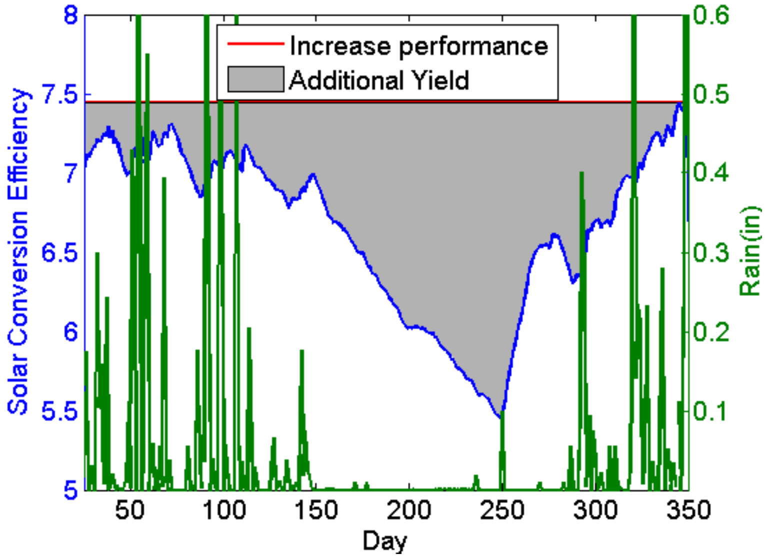

Fig 5. Additional yield if panel is always clean. Red line is expected performance with a panel that is always clean. Gray area is additional yield caused by always having a clean panel.

4. Conclusion

One year of power output from a PV site in Santa Clara, CA demonstrated how soiling decreases the efficiency of solar PV plants. Soiling effects were found to strongly depend on the dry exposure time of the panel. Soiling losses have their largest impact during the long dry summers. The losses caused by accumulation of dust were estimated to be -0.0021 per day in relative solar conversion efficiency. The PV site had a efficiency decrease from 7.2% to 5.6 % which is more than an order of magnitude larger than losses due to cell degradation (typically 0.5% efficiency loss per year or 0.14% in 108 days) [10]. After the rain event in the fall the efficiency increased to 7.1% a similar value to that observed in the spring further suggesting that dust had accumulated on the site.

For the poster presentation at the SolarPACES conference the complete database of 180 PV systems in California will be analysed and further analysis on determinants of soiling (geography, tilt, etc.) will be presented.

The California Solar Initiative database is unique in that production data from a large set of stations is publicly available and soiling losses could be determined without confidential information. While soiling effects in California were found to be relatively small and rarely warrant the additional expense of panel cleaning, sites in direct proximity to anthropogenic air pollution or natural events such as dust storms may experience more significant soiling.

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