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Soiling Losses for Solar Photovoltaic Systems in California

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Abstract

Soiling is the accumulation of dust on solar panels that causes a decrease in the solar photovoltaic (PV) system's efficiency. The changes in conversion efficiency of 186 residential and commercial PV sites were quantified during dry periods over the course of 2010 with respect to rain events observed at nearby weather stations and using satellite solar resource data. Soiling losses averaged 0.051% per day overall and 26% of the sites had losses greater than 0.1% per day. Sites with small tilt angles ($<5^o$) had larger soiling losses while differences by location were not statistically significant.

1. Introduction

With the rapid increase in the use of photovoltaic (PV) power in California, which has 47% of the installed PV capacity in the US, the optimal management and analysis of expected performance of PV sites becomes increasingly important. Soiling can have a large effect on efficiency during long droughts[1], which mainly occur during the summer season coincident with the largest solar resource. Dust from air pollution particles, sea salt, pollen, agricultural activity, construction and other anthropogenic and natural sources accumulates on the panels until it is removed either by rain or washing.

Research on soiling has primarily been conducted in the middle-east [2] due to the large aerosol loading in the air and the greater abundance of or plans for concentrating solar power plants that are much more affected by soiling. For a concentrating solar power desalination plant in Abu Dhabi, UAE soiling was found to be strongest during sandstorms in the summer season [3]. The transmittance of glass panels after 30 days of exposure in India decreased from 90% to 30% for horizontal and from 90% to 88% for vertical panels [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 analyzing soiling losses, the site selection criteria may have led to an overestimate of soiling losses.

The goals of this study are to quantify performance decrease due to soiling and to provide guidance on the necessity of cleaning solar panels in California. In Section 2 the PV power dataset and quality control are described and three different methods for identifying soiling losses on PV panels are introduced. Soiling results are presented, stratified by location and panel tilt, and discussed in Section 3. The conclusions are given in Section 4.

2. Data

2.1. California Solar Initiative Sites

Under the Performance Based Incentive (PBI) program of the California Solar Initiative (CSI) rebate payouts are based on AC energy output metering in 15 minute intervals [5]. The AC power produced from 194 San Diego Gas and Electric (SDG&E), 385 Southern California Edison (SCE), and 403 Pacific Gas and Electric (PGE) sites were obtained for the year of 2010. These data were then quality controlled one-by-one to eliminate sites that had more than 70 % missing data, large noise, or inverter clipping of power. In this way, 305 sites with high quality data were identified. The CSI database also includes the azimuth and tilt angle of the solar panels.

2.2 Solar Conversion Efficiency

The 15 minute data from the CSI database was aggregated over a day to obtain more robust efficiency estimates. The estimated solar irradiation from SolarAnywhere (SAW) was used to model the solar resource for each CSI 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% and no persistent error trends across the year [6]. Using the daily energy produced from the CSI site (P_{CSI}) and the daily incident solar energy modeled from SAW (P_{SAW}), the daily (relative) DC solar conversion efficiency (η_r) for the solar panels was calculated, controlling for the effects of temperature η_T and inverter η_{AC} efficiency as follows:

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

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

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 $\alpha = 0.5$ % K^{-1}, respectively. Inverter efficiency was modeled using a 3rd order polynomial versus power factor as in [9]. To be able to intercompare soiling effects between sites, η was then normalized by its average for the year to obtain a relative performance η_r.

2.3 Rain Data

Data from the California Irrigation Management Information Systems (CIMIS) were used to estimate the amount of rain at each CSI site. Hourly data from 134 CIMIS stations were obtained and quality controlled by examining the difference in daily rain versus the site distance for each station pair (not shown) leading to exclusion of one CIMIS station. Daily rain data were linearly interpolated from the 133 remaining CIMIS stations to the CSI sites. 90 CSI sites were outside the interpolation region and were excluded. Within the interpolation region all CSI sites were within 50 km from a CIMIS site indicating that the rain data was generally representative of the CSI sites.

A final quality control was conducted by visually inspecting plots of interpolated rain and η_r for each site over the course of the year. At 36 sites η_r exhibited a pronounced parabolic shape suggesting that the tilt angle in the CSI database was incorrect and these sites were removed from this study. This left 186 sites, 76 sites from PGE, 75 from SCE, and 35 sites from SDG&E. 14 sites were found to have a pronounced decrease in η_r during the summer, suggesting soiling, but η_r rapidly increased without a concurring rain event. These sites were assumed to have a washing system for the PV panel and 0.1 in rain events were manually added to the data.

2.4 Rain Events

Two main factors control how much soiling exists on a PV panel: the accumulation of dust which is a function of location and duration of exposure, and the removal of dust through rain. PV panels are naturally cleaned by rain, but the effectiveness of cleaning varies with the amount of rain. This was analyzed by averaging η_r 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. Consequently, only rain events after droughts of at least 31 days (similar to [1] who applied a 20-50 day "grace period") were considered for this part of the analysis (Fig. 1). Then, $\eta_a - \eta_b$ increased with rain amount from 0 to 0.1 in of rain and stabilized at larger rain amounts. This suggests a proportionality relationship for small rain amounts and a threshold of 0.1 in of rain beyond which the cleaning effectiveness does not increase.

Consequently, a rain event was defined as a day when more than 0.1 in of rain are observed and is assumed to restore the panel's efficiency to that of a clean panel. Rain storms with multiple consecutive rain event days were combined into one multi-day rain event.

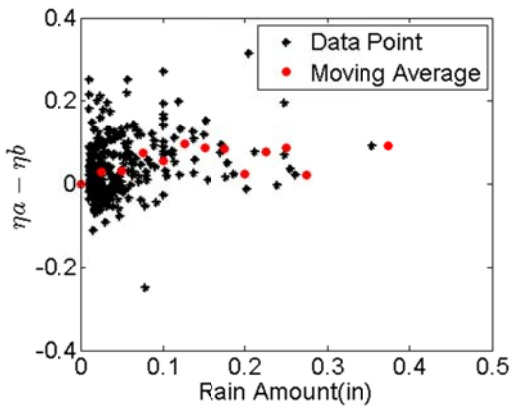

Fig. 1 Change in panel efficiency during a rain event after droughts longer than 31 days versus amount of rain for all CSI sites during 2010. The moving average is computed over bins of 0.02 in of rain.

2.5 Quantifying losses due to soiling

As demonstrated in Fig. 2a, large soiling impacts were observed at some sites. These soiling effects were particularly strong during the long summer droughts. At the site in Fig. 2a, there is a steady decrease in the efficiency of the PV plant after the last rainfall before summer (day 110). 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.

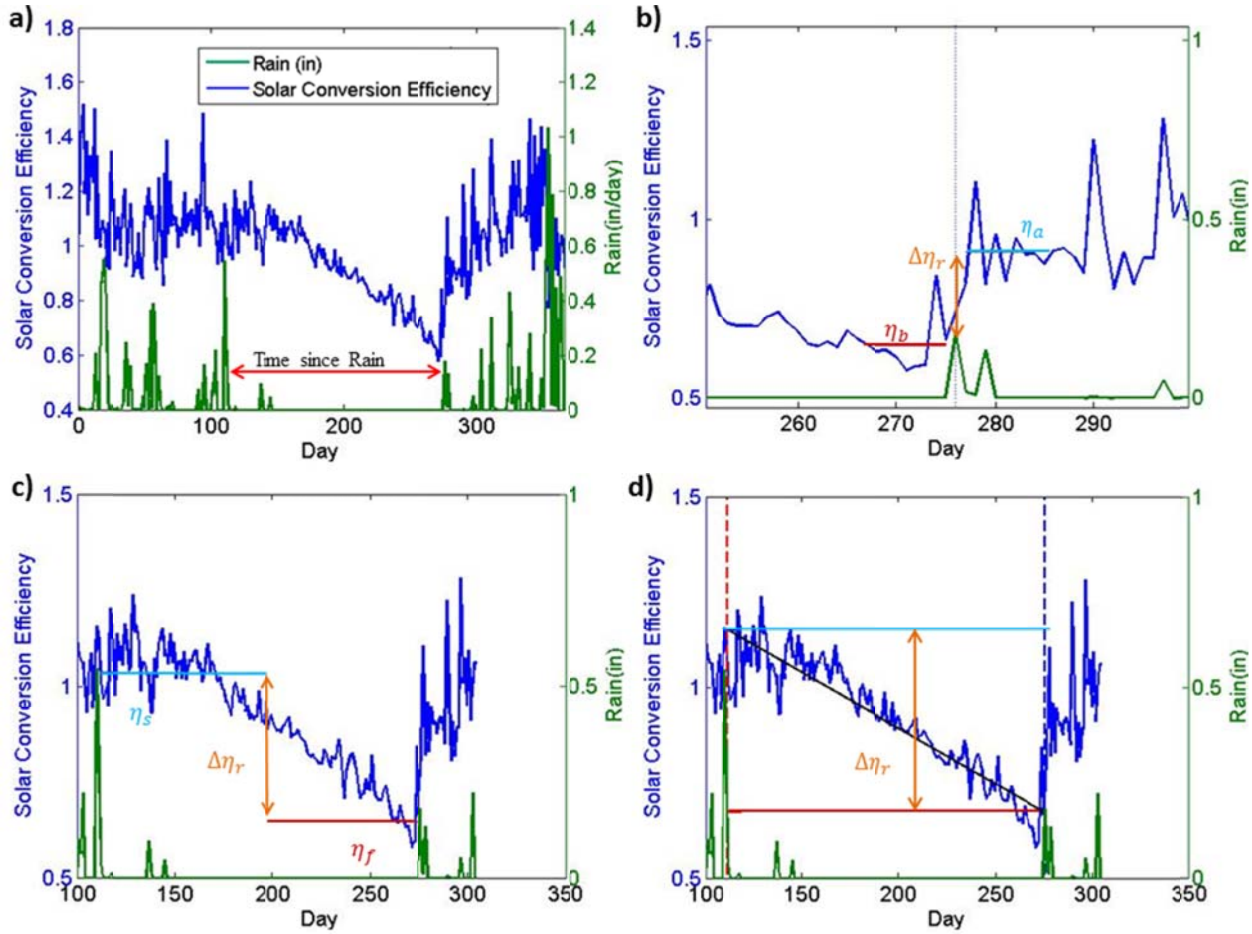

Fig. 2a) Timeseries of daily solar conversion efficiency η_r and daily rainfall for a 554 kW_{dc} PV plant in Hanford Kings, CA in 2010. Soiling losses are quantified through three different methods: b) Zoom in to before and after the first rain event following the summer drought. The weekly average solar conversion efficiency before (η_b in red) and after (η_a in blue) the rain event (vertical dashed line) are used to compute the soiling effect $\Delta\eta_r$. c) The weekly average solar conversion efficiency for the first week of the drought (η_s in blue) and the last week of the drought (η_f in red) are used to compute $\Delta\eta_r$. d) Linear regression of efficiency versus number of days since last rain in black. For consistency with the other methods $\Delta\eta_r$ is expressed as the first (blue) minus the last (red) value of the drought period and these data are used in Fig. 3.

Three different methods were used to identify the soiling losses. Method 1, which was used in analyzing the effects of rain amount (Section 2.4), uses the averages of the weeks before and after the rain event (Fig. 2b). Assuming that the panels are completely clean after the rain event, the amount of soiling that existed prior to the rain event causes an efficiency decrease of $\eta_b - \eta_a$ (the difference is now reversed since it refers to soiling losses and not recovered performance). The day(s) of the rain event are not included in the weekly averaging, rather the averaging occurs over the week before and the week after the rain event. The seven day averaging is used to reduce noise (e.g. from random errors in the satellite solar resource estimate in Eq. 1) and avoid occasional days of missing data right before or after the rain from impacting the analysis. Also days that had an efficiency above 1.5 or below 0.5 were excluded since large excursions are typically a result of an error in the solar resource model. The daily soiling losses for the drought period are calculated as $\eta_b - \eta_a$ divided by the days since the previous rainfall. The calculations for method 1 are demonstrated in Fig. 2b, where $\eta_b - \eta_a = -0.28$ and the soiling losses for the preceding 165 day drought period were -0.0017/day.

The second method - similar to the first method - uses weekly averaging, but the efficiencies averaged over the week after the previous rain event η_s and the week before the next rain event η_f are compared. Days that had efficiency above 1.5 or below 0.5 were also excluded from the average. Again the daily soiling losses for the drought period are calculated as $\eta_f - \eta_s$ divided by the days since the previous rainfall. This method can be observed in Fig. 2c, where $\eta_f - \eta_s = -0.41$ and the soiling losses for that drought period were found to be -0.0025/day.

The final method calculates soiling losses by applying a linear regression fit to the entire data during the drought period. The slope of the best fit line is then assumed to be the daily soiling for that drought. For quality control, droughts when more than 20% of the efficiency data were above 1.5 or below 0.5 were excluded. Also efficiency data greater than 1.5 or less than 0.5 were not used in the fit. This method can be observed in Fig. 2d, where the soiling losses for that drought period were found to be -0.0029/day.

Each of these methods has particular benefits and assumptions. The method of choice in this analysis is method 3, which was previously shown to quantify soiling [1]. Method 3 only includes the assumption 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. Method 3 also uses the largest amount of data points. Method 2 uses similar assumptions but is limited because it uses a smaller amount of data. Finally method 1 assumes that the panel is equally clean at the start of the drought period and after the next rain event such that differences in efficiency are only related to soiling during that drought period. For long droughts, method 1 has the advantage that the data used for soiling calculations fall within a continuous 2 week period such that panel degradation and seasonal errors in the SAW resource model become minimal. Overall little difference in the overall soiling losses was observed for the different methods (see Fig. 4 later) indicating that the results are robust.

3. Results and Discussion

3.1 Average soiling losses

Fig. 3 demonstrates the soiling losses as change in relative solar conversion efficiency versus time between rain events as calculated from method 3 (Fig. 2d) for all rain events at every site. The slope of the linear regression gives the average daily soiling losses as 0.00051 per day in relative solar conversion efficiency. In other words, if a site had an average efficiency of 15% its efficiency would decrease to 13.89% after a 145 day drought, which is the average of the longest drought period for each site.

To calculate the losses for each site, a linear regression is fit to the scatter plot of the soiling losses and drought period for each site. Fig. 4 shows the distribution of soiling losses for the 186 sites for each of the three methods. Some sites have a positive soiling losses (or soiling gains) which indicates that essentially no soiling occurred and that small errors in the solar resource model caused a positive slope in Fig. 2d. There is also a possibility that a few sites had automated washing systems (or meticulous owners/operators) which kept the panels continuously clean, but overall these scenarios are unlikely. Since the soiling losses are consistent between the three methods, the linear regression method (method 3) is used for the remainder of the paper.

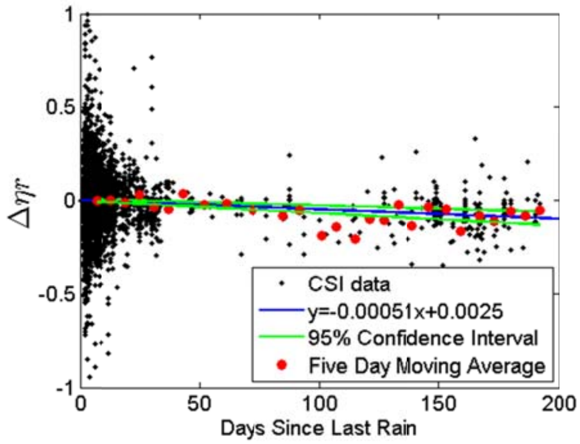

Fig. 3 Change in efficiency during a drought period (method 3) versus time since last rain event at all CSI sites. 12 outliers smaller than -1 are not shown. Red circles show the average for each day. A linear regression fit with 95% confidence interval is applied to the data.

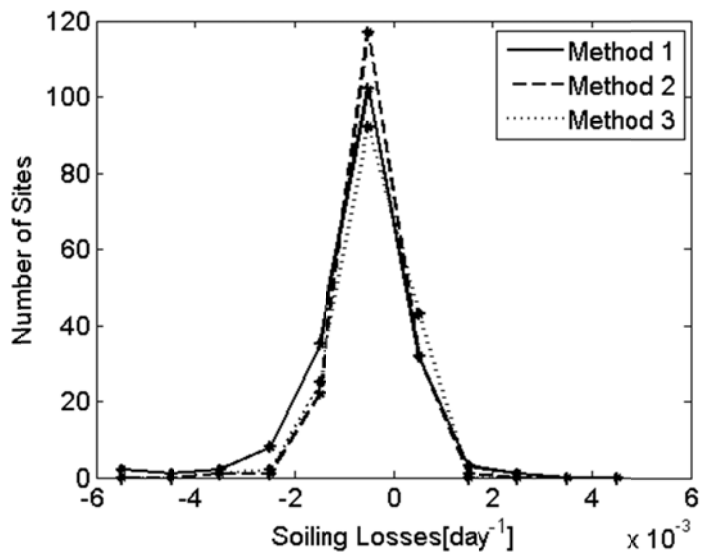

Fig. 4 Histogram of the soiling losses at all CSI sites as computed from the three different methods (Section 2.5).

3.2 Tilt angle and Geographical Location

48 CSI sites were identified to have losses greater than 0.001. To identify why these sites had larger losses the tilt angle and the location of the sites were investigated.

Fig. 5 shows the mean soiling losses for tilt angles from 0-5, 6-19, and greater than 20 degrees. The average soiling losses for sites with a tilt angle smaller than 5^{o} is five times that of the rest of the sites as shown in Table 1.

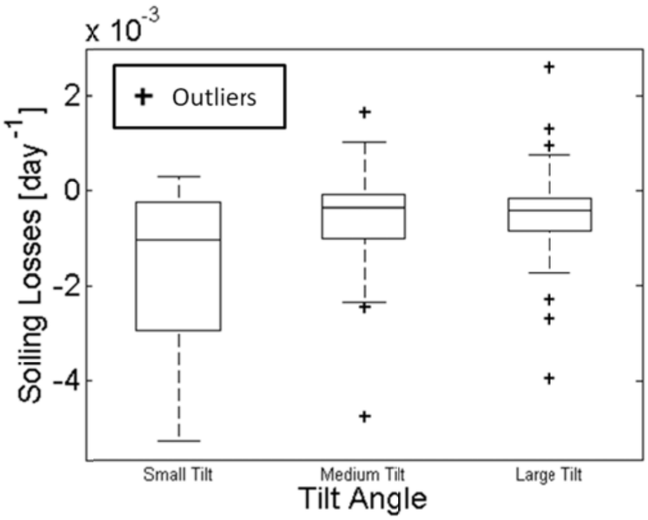

Fig. 5 Box-Whisker plot of the distribution of soiling loss (method 3) for different tilt angles. The bin from 0 to 5^{o} contains 12 sites, 102 sites have tilts from 6^{o} to 19^{o} and 88 sites have tilts equal to or greater than 20^{o}.

A map (Fig. 6) and table (Table 2) of soiling losses by site was used to identify clustering of large soiling sites to identify patterns due to e.g. air pollution or farming. Large soiling appears to be more prevalent in the Los Angeles Basin and the Central Valley area, but the differences are not statistically significant at the 5% level.

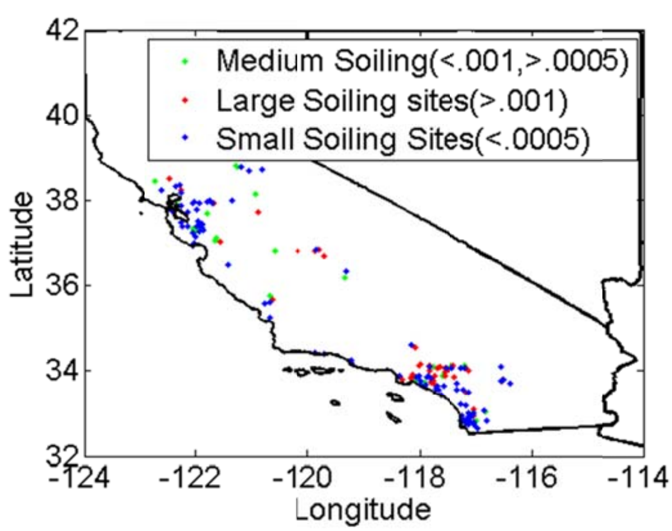

Fig. 6 Map of CSI sites and their soiling losses per day.

4. Conclusion

One year of power output from 186 PV sites demonstrated how soiling decreases the efficiency of solar PV plants. The accumulated soiling effects were found to depend primarily on the time since the previous rainfall (Fig. 3) and supported previous findings that soiling can be modeled as a linear degradation [1]. On average losses were 0.00051 per day in relative solar conversion efficiency. Over an average 145 day summer drought this results in a 7.4% loss in efficiency. For a 15% efficient PV panel soiling losses over a 145 day drought would decrease the efficiency to 13.9%. For reference, this is more than an order of magnitude larger than losses due to cell degradation (typically 0.5% efficiency loss per year or 0.19% in 145 days) [10].

Using a similar method and in a similar geographical region [1] had found four times larger soiling losses of 0.002 per day. We hypothesize that the elimination of sites with R^2 values less than 0.7 in [1] as well as the limited amount of sites examined caused their soiling losses to be biased high. Sites with small soiling losses tend to have smaller R^2 since random errors in the solar resource estimates dominate over the correlation between soiling and time since last rain event.

The distribution of soiling by site is skewed with a few sites showing very large soiling losses. Of the 186 sites, 48 were found to have soiling losses greater than 0.001 per day. One factor for these large soiling losses was the tilt angle: sites with a tilt angle less than 5 degrees had on average 5 times the soiling losses than the other sites. This finding supports that more soiling accumulates on a horizontal panel as previously found for glass plates in [4]. The large variability of the data for larger tilts and inconsistent regional trends suggests that soiling is very site specific. For example some sites could have high winds that are able to clean low tilt panels while high tilt panels are better cleaned by gravity. Sites in the Los Angeles basin and the Central Valley Area were found to have larger soiling losses but the differences were not statistically significant to conclusively determine the location as a cause.

How much additional solar energy could be harvested through panel washing? Manual washing is expensive and typically only scheduled during the summer drought. We estimates impacts of one annual washing based on the average soiling losses for each site (Fig. 4) and the one half the length of the summer drought for each site. On average, the sites would have yielded 0.81% more annual energy if they had been washed halfway through the summer drought period while some sites would have realized solar energy production increases of up to 4% (Fig. 7).

If an automated cleaning system was installed to clean the sites regularly, larger energy gains would be possible, on average 9.8% 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. 8) is then calculated as the integral between the efficiency of this clean panel and the actual observed efficiency.

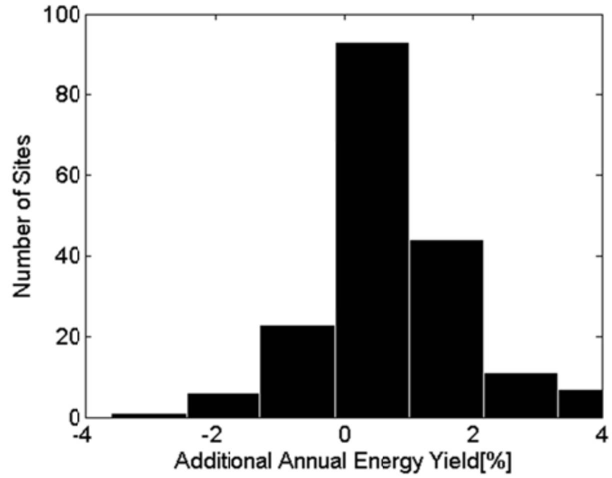

Fig 7. Histogram of the additional annual yield possible for each site by cleaning the panel once per year halfway through the summer drought period.

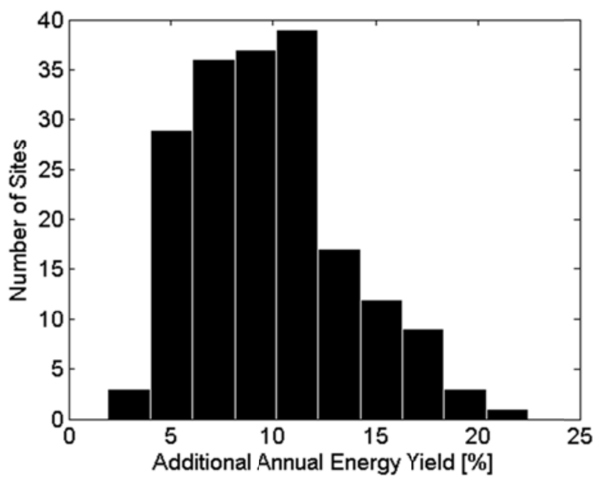

Fig 8. Histogram of the percent additional yield if the panel was always clean.

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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Tables

Table 1. Soiling losses stratified by tilt angle.

	Number of Sites	Mean Soiling Losses [10^{-4} day^{-1}]	Fraction of sites with soiling > 0.1/day [%]
Tilt < 5 ^{o}	12	-18.0	50
5 ^{o} < Tilt < 19 ^{o}	90	-5.2	24.4
Tilt > 20 ^{o}	84	-5.3	23.8

Table 2. Soiling losses stratified by geographical region.

	Number of Sites	Mean Soiling Losses [10^{-4} day^{-1}]	Fraction of sites with soiling > 0.1%/day [%]
San Francisco Bay	47	-4.8	12.8
Central Valley	29	-5.8	24.1
SCE	75	-8.3	41.3
SDG&E	35	-2.7	11.4