THE EFFECT OF SOILING ON LARGE GRID-CONNECTED PHOTOVOLTAIC SYSTEMS IN CALIFORNIA AND THE SOUTHWEST REGION OF THE UNITED STATES

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ABSTRACT

The accumulation of dirt on solar panels ("soiling") can have a significant impact on the performance of PV systems in regions where rainfall is limited for a dry season of several months. This effect is magnified where rainfall is absent in the peak-solar summer months, such as in California and the Southwest region of the United States. This paper describes the effects of soiling on energy production for large grid-connected systems in the US and presents a model for predicting soiling losses.

INTRODUCTION

Although the energy lost to soiling of PV systems is of great interest to system owners and operators, there is little information currently available regarding soiling. Much of the information available is applicable only to the specific location in which the testing was conducted, and there is a need to characterize soiling at a more general level. This kind of general study is best conducted by surveying the performance of a number of PV systems in different regions and different operating environments.

APPROACH AND MODEL DEVELOPMENT

PowerLight monitors over 250 photovoltaic systems on a daily basis from our Berkeley, CA headquarters. The 15-minute remote monitored data from these sites was the primary source of information regarding rates of soiling for this study.

Measured PV system performance trends show a gradual but marked decrease in system performance through the dry season for systems in arid climates. System performance returns to normal levels after a period of rain following the dry season, as illustrated for a typical Southern California rooftop system in Figure 1.

Most existing PV system simulation programs assume a PV module soiling loss that is constant through time. [3,4,5] Our observations of measured performance suggest that performance losses due to system soiling are not constant through time, rather they depend on the amount and frequency of rain that falls on the system.

The purpose of the study described here is to develop a model that approximates the soiling pattern observed in measured performance data to improve the accuracy of simulations.
Questions critical to the development of such a model include:

1. For how long after a rainfall do modules stay relatively clean?
2. How fast does dust accumulate on PV module surfaces? How does this rate vary between regions and within different environments?
3. How much rain is required to thoroughly clean a PV system?

As in Figure 1, the observed decline in system performance over the dry season appears approximately linear. Although all systems appear to have similar patterns of performance degradation and recovery, the rate of decline in system performance through the dry season is not the same for all systems; it appears to be influenced by the level of activity in the system's immediate environment. These facts suggest that the effects of soiling on PV system performance may be accurately predicted using a linear model of decreasing system performance over time between significant rainfall events, perhaps with some delay between a rainfall and the application of the soiling loss. Additionally, different rates of system performance decline will apply for different locations.

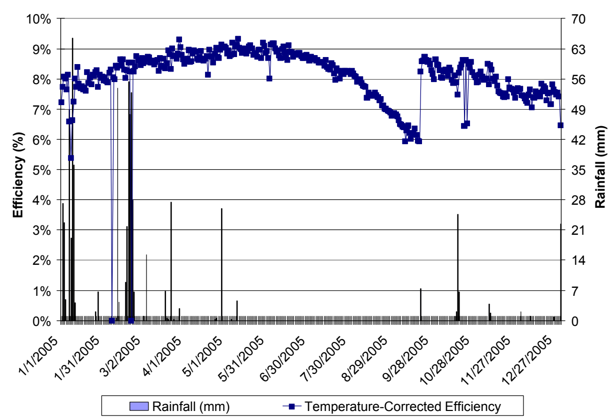

Figure 1: 2005 Daily η_{temp} for a roof mounted PV system in Los Angeles plotted with daily rainfall amounts

PRELIMINARY STUDY WITH 10 SAMPLE SYSTEMS

To evaluate the validity of a linear approach to approximating soiling losses, a linear regression was applied to performance data from 10 systems for the dry season of 2005. The 10 sample systems were chosen from various climates and environments to ensure a representative cross-section of system locations and soiling effects.

For calendar year 2005, four different daily performance metrics were plotted for each system as a function of time along with measured rainfall data. The start and end dates of the dry period for each site were determined by inspection of the performance and rainfall charts; the performance metrics were then plotted over the dry period only and a linear curve fit was used to determine the slopes of the resulting lines, or the Measured Soiling Rates (R_{ms}).

For the 10 test sites, the linear curve fits (R^2) were evaluated to determine the extent to which the soiling effect is linear. An R^2 of 0.7 or higher was considered sufficient to support the use of a linear approximation. The actual average of all curve fits for the 10 sample sites was 0.835. Table 1 details the R^2 values for all four performance metrics for each of the 10 sample sites. The best fits for each system are highlighted.

Table 1: Linear Fit R^2 values for 10 Sample Systems

System	R^2 kWp	R^2 Efficiency	R^2 Temperature-Corrected Efficiency	R^2 OPI
SC Urban 1	0.867	0.931	0.942	0.925
SC Urban 2	0.823	0.846	0.951	0.855
SC Suburban	0.822	0.894	0.916	0.893
NC Urban 1	0.943	0.946	0.916	0.915
SC Urban 3	0.771	0.837	0.904	0.837
CV Suburban	0.866	0.885	0.897	0.852
NC Suburban	0.779	0.668	0.668	0.645
CV Urban 1	0.774	0.786	0.781	0.688
NC Rural	0.705	0.838	0.831	0.830
CV Urban 2	0.707	0.820	0.820	0.830

For 6 of the 10 test sites, actual measured energy was compared to the predicted energy using the four R_{ms} to asses the predictive accuracy of the 4 metrics. Total system conversion efficiency corrected for module temperature, η_{temp}, was chosen as the metric for use in the main study because of its accuracy of energy prediction, high R^2 values, and ease of implementation. The formula for η_{temp} is as follows:

$$\eta_{temp} = \left[\frac{KwhAC}{A \times Gpoa}\right] \times \left[1 + \beta\left(T_o - T_m\right)\right]$$

Where:
kWhAC = total measured AC energy production (kWh)
A = total module area (m^2)
Gpoa = total measured global insolation on the plane of the array (kWh/ m^2)
T_o = reference temperature (STC) (^oC)
T_m = average module temperature (calculated per [1]) (^oC)
ß = module temperature coefficient of power (%)

Figure 2 shows the regression fit for an urban Southern California system during the dry summer period using η_{temp}. The results of the preliminary study support the use of linear approximations of performance degradation due to system soiling and suggest that η_{temp} gives the most accurate approximation of performance degradation over time.

Soiling Events and Anomalies

Close inspection of the sample sites in the preliminary study showed that about half exhibited a "grace period" after the last spring rain where soiling was negligible, or a period during which soiling rates appeared slower than in the later part of the dry season. Figure 1 illustrates this effect. The last significant rainfall of the spring occurred in late April, and the rate of performance decline did not start to increase appreciably until the middle of June. Observed grace periods for those sites that exhibited this behavior was 20-50 days. However, just as many sites did not exhibit grace periods.

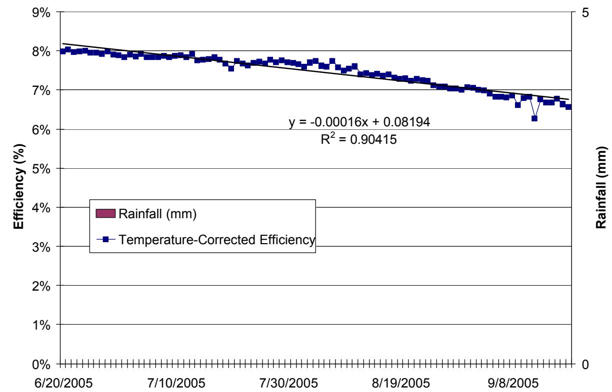

Figure 2: Dry season performance for system SC Urban 3

Another example of non-uniform behavior observed in the preliminary study was the unpredictable nature of system performance following a very light rain at the end of the dry season. In some cases, a light rainfall can cause system performance to fall sharply. For example, a performance drop after a light end-of-summer rain was noted for all of the Northern California systems in the preliminary study.

The anomalous behaviors described in this section suggested that further investigation of the amount of rain needed to clean systems was necessary, and that care should be taken when selecting the beginning and end of the defined soiling period to avoid unpredictable end-of-season behavior.

MAIN STUDY: 250 SYSTEMS

Soiling Rate Analysis

In order to determine appropriate soiling rates for the various climates and environments considered, a software application was created to automate the calculation of the slope and the R^2 of the linear regression of η_{temp} over the 2005 dry season for all of PowerLight's monitored systems (approximately 250 systems). The year 2005 was chosen to maximize the amount of data available for this analysis. Each of PowerLight's systems was assigned a geographical region and local environment type.

For each region, the dry season was defined based on the last rainfall of the rainy season and first rainfall after the dry season recorded at local airports by NOAA. [9] These slopes of efficiency over time were normalized using the baseline η_{temp} for the system to produce a percent performance loss rate applicable to any PV system. (The baseline efficiency is an average of η_{temp} for the first seven days of the dry season.)

For all regions with significant rainfall (at least once per month), no decline in performance was measurable using the linear method discussed above. Levels of performance for systems in these regions remain relatively constant throughout the year, confirming that soiling of PV systems in these regions does not seriously influence system energy production. Such regions in this study include: Germany, Hawaii, and the U.S. Mid-Atlantic, Northeast, Southeast, and Midwest.

Systems in the California and Desert Southwest regions all showed the characteristic gradual decline in performance described above. Regression slope and R^2 values for all systems in these regions were summarized and checked for quality. Any system with an R^2 value less than 0.7 was excluded from the rate analysis. A total of 46 systems remained in the data set after all systems in regions with frequent rain and all systems with unacceptable curve fits (R^2 value less than 0.7) were excluded. Each of these 46 systems was categorized by its region and environment.

For each combination of region and environment represented in the final 46-system data set, the average of the soiling loss rates of the systems was calculated. Figure 3 summarizes the average daily performance loss for each region and environment based on these 46 systems. Average rates of loss were found to be anywhere from 0.1 – 0.3% per day.

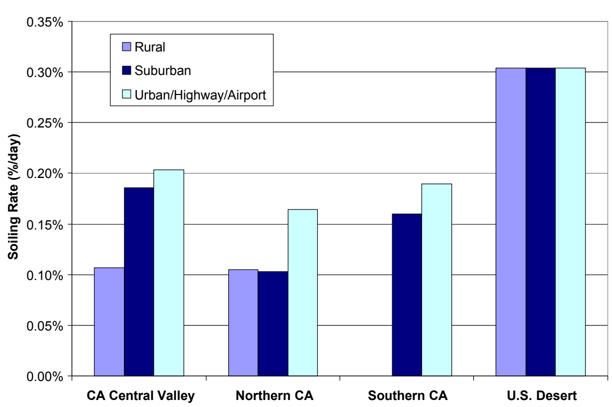

Figure 3: Average daily soiling loss by region and environment

System orientation was investigated as a possible factor influencing soiling rates; however, data in this study suggested that system orientation does not greatly influence the rates of soiling. Figure 4 shows the regression fit for a single-axis tracking system in the Desert Southwest.

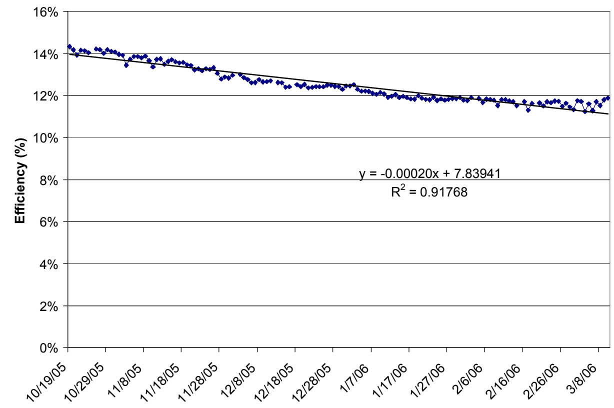

Figure 4: Dry Season performance for rural single-axis-tracking system in the U.S. Desert Southwest

Amount of Rainfall to Clean Modules

Previous studies have found that 0.2in (5mm) of rainfall is sufficient to clean photovoltaic systems [2]. However, analysis of our systems showed that some systems require significantly more rainfall to completely clean the modules. Figure 5 shows 2005 measured efficiency and precipitation of a photovoltaic system in Northern California. Several rainfall events in the Fall above 0.2 inches (5 mm) failed to clean the system. The efficiency continued to drop until a rainfall event on December 1 of 0.82 inches (20 mm) that cleaned the system, increasing the efficiency from 7.5% to 12.5%, or an increase of 40%.

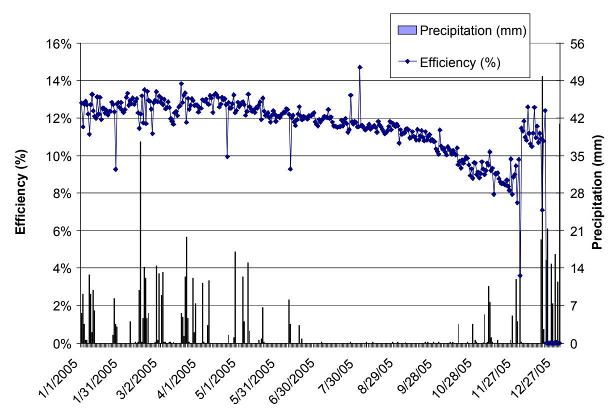

Figure 5: 2005 daily efficiency and rainfall for a representative system in Northern California

In order to better quantify this effect, the efficiency increase of all systems in each region was analyzed as a function of the amount of rainfall. Efficiency increase was calculated by subtracting the average system efficiency for the 7 days preceding the rainfall from the average system efficiency for the 7 days after the rainfall. The rainfall events were binned into the following categories: 0.2 to 0.3, 0.3 to 0.4, and greater than 0.4 inches over one day. Table 2 shows the results of this analysis.

As indicated by the large standard deviation and variation in the minimum and maximum percent increase in performance after rainfall events, there is not a clear amount of rainfall that will clean all systems. In fact, this data further confirms that system efficiency can decrease after a light rainfall. It is likely that the intensity of the rainfall influences whether or not the system is sufficiently cleaned, but this was outside the scope of this study.

Table 2: System Efficiency Percent Increase as a function of rainfall

	7-day Average Efficiency Increase (%)			
Rainfall Level	Avg	Max	Min	Stdev
Southern California				
0.2 - 0.3	6%	44%	-23%	18%
0.3 - 0.4	3%	17%	-8%	6%
> 0.4	5%	27%	-7%	7%
Northern California				
0.2 - 0.3	6%	77%	-46%	38%
0.3 - 0.4	10%	45%	-8%	12%
> 0.4	7%	80%	-79%	36%
California Central Valley				
0.2 - 0.3	3%	41%	-47%	12%
0.3 - 0.4	10%	34%	-24%	15%
> 0.4	0%	40%	-61%	18%
U.S. Desert / SouthWest				
0.2 - 0.3	6%	56%	-8%	14%

For the purpose of this study, the threshold amount of rain needed to clean a system was selected as the bin amount resulting in the largest average percent increase. These values are highlighted in Table 2.

Model Development

Based on the results of our study, an empirically derived model of soiling-related PV system performance degradation was developed. The model approximates field conditions by eliminating soiling-related losses in the rainy season and incrementally increasing them throughout the dry season.

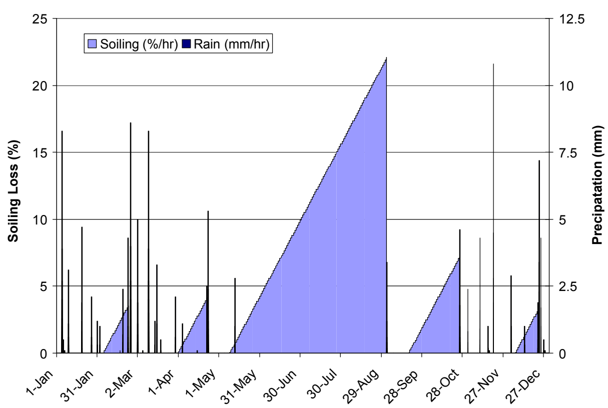

Figure 6: Hourly soiling loss for typical year weather in San Diego, CA

The model contains three key elements:

1. Soiling rate. This is an empirically-derived factor that describes the pace of performance degradation due to system soiling. It is specific to the site's location.
2. Cleaning threshold. This is the amount of rain required to fall in one day to fully clean the PV system
3. Grace Period length. This is the number of days that a system remains relatively clean after the last rain that meets the cleaning threshold.

Implementing this model in the PVGrid solar electric system simulation program requires that rainfall information be input along with the traditional solar radiation data. The soiling rate model sets the system soiling loss factor for each hour in the simulation. Figure 6 shows an example of the hourly soiling loss applied by the soiling rate model for a typical year in San Diego, CA.

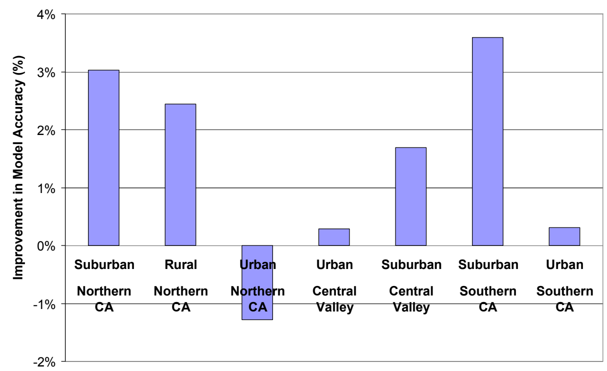

Figure 7: Modeling accuracy improvement created by the soiling rate model

Model Validation

In order to validate PowerLight's new soiling rate loss model, the model's logic was incorporated into the code of PowerLight's existing solar electric system simulation program, PVGrid. Seven existing PowerLight systems were selected for use in the model validation; measured weather data for each of these systems for 2005 was compiled into a data file for use in the new PVGrid simulation program [5]. The new PVGrid simulation program was then run for each of the selected systems using measured weather data and as-built system configurations as the model inputs. The original PVGrid model (using a constant 5% annual soiling loss factor) was also run for these sites as a control/comparison.

Figure 7 summarizes the improvement in modeling accuracy created by the soiling rate model for each of the systems chosen to validate the new PVGrid model. A positive value indicates that the soiling rate method results in an estimate of energy production that is closer to the measured production for the site than the traditional soiling loss method; a negative value indicates that the soiling rate method results in an estimate of energy production that is less accurate than the traditional method. Annual energy estimates were better with the soiling rate model than with the traditional loss factor method in six of the seven cases.

Figure 8 shows daily energy measurements and predictions for one of the validation sites and clearly shows the improved accuracy of the soiling rate model.

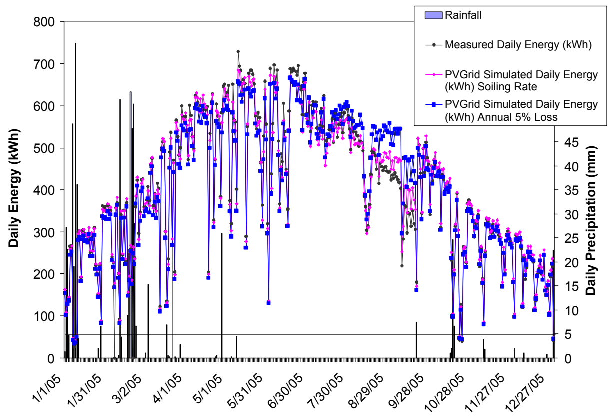

Figure 8: 2005 daily measured and simulated energy for an urban system in Southern California

Model Results

The new soiling rate model implemented in PVGrid was used to determine the annual soiling loss for a “generic” photovoltaic system located in each region and environment considered in the study. Typical Rainfall data was obtained from Meteonorm for this analysis. [8] Figure 9 shows that the average annual loss of energy due to system soiling varies from 1.5% to 6.2%. In the last 30 days of the dry season, the soiling rate model predicts system soiling losses of up to 27%.

Figure 10 shows how the soiling rate model results effect the annual and monthly energy predicted for a typical flat photovoltaic system located in Los Angeles, CA and how the soiling rate model compares with a traditional assumption of 5% loss that is applied annually.

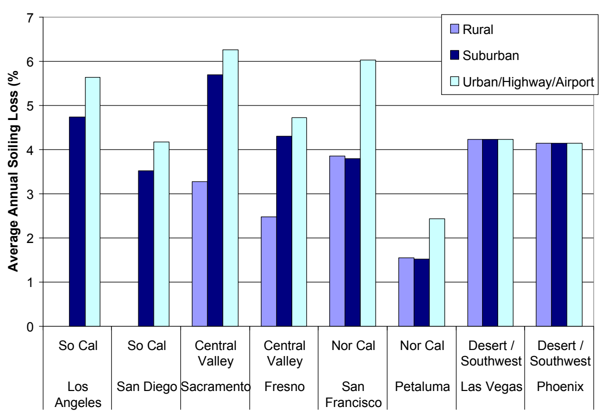

Figure 9: Average annual soiling loss predicted for typical year weather

CONCLUSIONS AND FURTHER RESEARCH

This study presents a new model for predicting the energy loss of photovoltaic systems from the accumulation of dirt and particulate matter on PV modules. This model was empirically derived and incorporated into an hourly energy simulation program that uses TMY2 data files and typical rainfall data to predict energy performance. It found that photovoltaic system efficiency declines by an average of 0.2% per day without rainfall in dry climates. This daily loss finding equates to an annual energy loss between 1.5 - 6.2% depending on system location.

Most existing PV system simulation programs assume a PV module soiling loss that is constant throughout the year [3,4,5] The soiling rate model presented in this paper is an improvement upon this standard assumption and applies the losses when they occur during the dry season in California and the Desert Southwest.

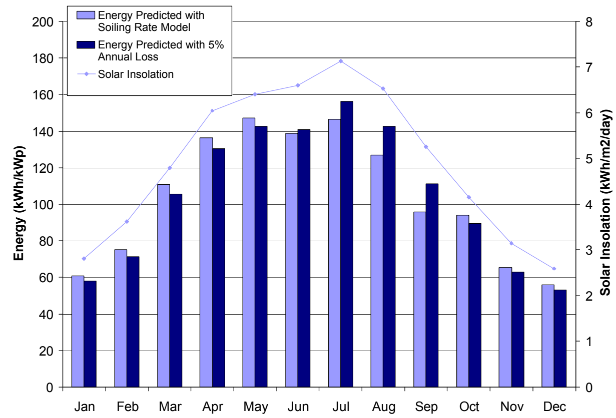

Figure 10: Monthly predicted energy from soiling rate model and traditional soiling loss assumption

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