THE EFFECT OF SOILING ON PHOTOVOLTAIC SYSTMES LOCATED IN ARID CLIMATES

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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 arid regions where rainfall is limited for several months. This is an important effect as many arid regions, such as the Southwest region of the United States and Southern Europe, are growing markets for solar energy projects. In order to evaluate soiling's economic impact on revenue and determine the economically optimum time to manually clean a system, one must understand the impact of soiling on system performance degradation in terms of both rate and severity. This paper expands on previous work (Mitchell *et al.* 2006) in which a predictive model was developed to quantify the energy lost to soiling on PV systems. [1]
Keywords: Performance, Degradation, PV System, Soiling

1 INTRODUCTION

Soiling in PV systems is one of the largest losses under the control of the system operator. However, cleaning of PV arrays, especially large commercial roof-top or utility-scale arrays, can cost a significant amount of money for labor and water. Consequently, it is important to characterize and predict the rate and severity of soiling to enable economic optimization of array cleanings.

In 2006, Mitchell, et al undertook a comprehensive review of system performance degradation due to soiling for over 50 large, grid-connected PV systems (including flat, tilted and tracking mounting systems) in arid regions of the U.S. [1] In this study, system performance during the year 2005 was assessed with respect to measured rainfall and number of manual cleanings at the respective system locations. Soiling rates, or the rate at which the the system's output power at STC declines each day due to the accumulation of dirt on the panels, were approximated as linear over time for periods without rainfall. Systems were divided into groups based on region and local environment to study the variance in soiling rates between locales. Average soiling rates were determined for each region/environment pair and were used to develop a predictive model for annual PV system soiling losses based on the soiling rate and average annual local rainfall.

The results of this study and our predictive model indicate that average performance loss due to soiling in dry climates occurs at a rate of 0.0011 kWh/kWp/day without rainfall. This equates to an annual energy loss of between 2-6% depending on the region and environment (see Figure 1). The predictive model was validated using measured system performance data for the year 2005 and was found to improve model accuracy by up to 3.5% depending on the region and environment (compared to a traditional soiling loss assumption in the model of a constant 5% throughout the year). On average, model accuracy, or the degree to which the yield predicted by the model matched actual production, improved by 1.5%.

In order to further validate the model, we undertook a controlled study of soiling losses at a convenient site in the Los Angeles area of Southern California. This paper describes this controlled study and its results, and suggests areas for further investigation.

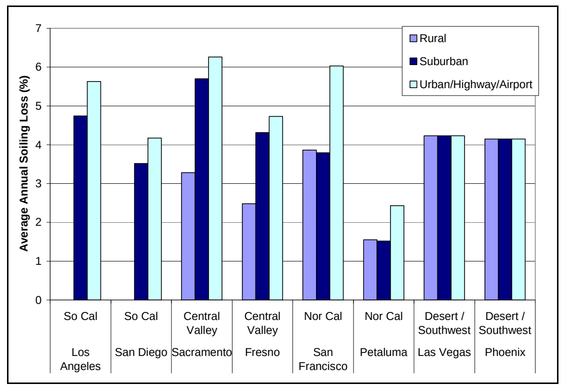

Figure 1: Average Annual Soiling Loss Rates [1]

2 SOILING STUDY DESIGN AND RESULTS

2.1 Study Site Description

Our controlled study of soiling losses was conducted in Southern California at a site where several identical photovoltaic systems were installed on the roofs of buildings in a commercial office park. Figures 2 and 3 illustrate the site and array layouts at the study location.. Three of the five buildings have identical size, layout and orientation of roof-top equipment, ensuring that wind patterns around these three PV arrays would be very similar. Therefore these three systems with long N-S axes were chosen for the study.

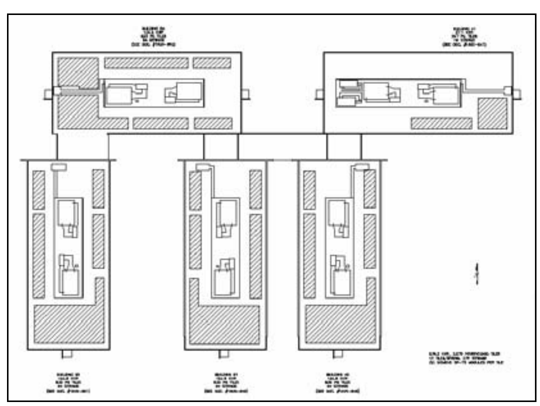

Figure 2: Array layout at study location

Figure 3: Aerial photograph of study location

The three PV systems used in this study all have identical specifications. Installed in February 2003, the systems each consist of 1,664 Siemens SP-75 laminates (e.g. frameless modules) mounted on SunPower's PowerGuard insulated roofing system and connected to the building's electrical grid through a Xantrex PV-100 AC-to-DC inverter.

The systems are continuously monitored using SunPower's standard commercial data acquisition system (DAS), which consists of revenue-grade AC energy meters for each inverter as well as an on-site meteorological station including irradiance, ambient temperature and wind speed sensors. Total energy, average irradiance, temperature and wind speed data is recorded at 15-minute intervals and stored in an SQL database for monitoring and analysis.

2.2 Study Procedure

The objective for this study was to evaluate the difference in annual energy produced by the three identical systems under different cleaning regimens. In Southern California, rainfall patterns are quite predictable, with rainfall coming to a stop in April or May and only starting again in late September or early October. In their previous study, Mitchell et al [1] noted that system performance held relatively steady during the rainy season in arid climates, suggesting that during the rainy season soiling losses are kept to a minimum (for this study, losses during the rainy period are assumed to be negligible). They also noted a short "grace period" during which soiling rates were negligible immediately after the last rain. Our study used these observations to determine a manual cleaning schedule for each of the three systems.

The last significant spring rain in 2006 occurred on May 22, 2006. Assuming a "grace period" of about two weeks, we expected the systems to begin soiling in mid-June and that the first fall rains would occur the second or third week of October. Splitting that time period into rough thirds, two cleanings were scheduled, one for July 17, 2006 and another for September 7, 2006. On July 17, only the system called A2 was cleaned. On September 7, systems A2 and B1 were cleaned, while system B3 was left unwashed. Thus, system A2 was washed twice, system B1 was washed once, and system B3 was left unwashed throughout the arid summer months.

System cleaning was performed by a local window-washing firm in the Los Angeles area. The cleaning crew used hoses with "tucker pole" attachments. A tucker pole is a long hollow pole with a hose fitting on one end and a soft bristle brush on the other. Water flows through the pole and out of the bristle brush, which is then used to agitate the water on the surface being cleaned to ensure a thorough wash. Figure 4 shows the cleaning crew in action, while Figures 5 and 6 show before and after photographs of the modules.

Figure 4: Array washing crew

Figure 5: Modules prior to cleaning

Figure 6: Modules after cleaning

2.3 Study Results

For this study, the twice-washed array (A2) was considered the baseline. Energy losses due to soiling for system A2 could not calculated explicitly, but for the purpose of this study, we assume that the losses this system suffered were small. Figure 7 shows a plot of daily system performance index for the three systems in the study, where performance index is calculated as the measured AC energy from a system divided by the expected energy for that system (expected energy calculations take measured insolation and temperature into account but do not include soiling loss assumptions). The effectiveness of array cleanings is clear, as the performance index for the system that was washed twice at strategic times during the dry season remains relatively constant. The first significant rain of the autumn is evident as well; it occurred on October 13, 2006.

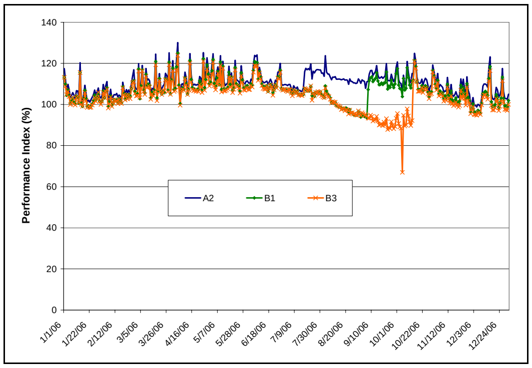

Figure 7: System Performance Indices 1 Jan – 31 Dec 2006

Table 1 summarizes the measured energy from each of the three systems in the study and compares the energy generated by system A2 (two cleanings) with the energy generated by the other two systems. System B1 generated 3.5% less energy than system A2 and system B3 generated 5.1% less energy than system A2. If we assume that the soiling loss on system A2 was negligible, then we can conclude that the energy loss due to soiling at this location in 2006 was 5.1%.

Table 1: Measured energy and soiling loss estimates

System	Number of Cleanings in 2006	Measured 2006 Energy (kWh)	Estimated Energy Lost to Soiling (kWh)	Estimated Annual Soiling Loss (%)
A2	2	157,405	0	0.0%
B1	1	152,188	5,217	3.3%
B3	0	149,451	7,954	5.1%

It should be repeated that system A2 is considered the baseline for convenience. The controlled part of this study took place from May – October 2006, with no further cleaning of any systems after October. Although the level of soiling present on system A2 was much smaller than the other two systems, there was still some soiling on this system that we have not quantified. This is evident after the first wash of system A2 in July, where it is evident that its performance improved slightly. Further, the winter of 2006-2007 turned out to be much drier than usual, with record low levels of rainfall. You can see that performance levels for all three systems fell between October and the end of December, an unusual pattern for this time of year, and one that suggests that the energy lost to soiling for all three of the systems was higher than in most years. This helps to illustrate the variability of soiling experienced even at the same site from year to year. More work is needed over longer study periods to help quantify these effects more fully.

3 ECONOMIC EVALUATION

Table 2 summarizes a simple economic cost/benefit analysis for this study (all values are expressed in U.S. Dollars). The cost to clean these roughly 100 kWp systems was $800 per cleaning. System A2, which was cleaned twice, produced nearly 8,000 kWh more energy than the system that was not cleaned (B3); system B1, cleaned once, produced approximately 2,700 kWh more than B3. Based on these cleaning costs and energy benefits, we conclude that it is not worth cleaning systems in this region if the value of the energy is simply the average avoided energy cost. However, for new systems in California installed under the California Solar Initiative incentive program, cleaning a system twice during the dry summer period increases total system revenue by $1,500 per 100 kWp capacity installed in Los Angeles, CA. The lucrative European feed-in tariffs make system cleaning even more economical, with a twice-annual cleaning increasing revenue by $3,000 per 100 kWp capacity installed in Los Angeles, CA (or in another location with similar solar resource.

Table 2: Economic analysis summary (per 100 kWp in Los Angeles, CA – annual insolation = 2,055 kWh/m^2)

			Economic Benefit/(Cost) of Cleaning Regimen		
Number of Cleanings in 2006	Cost to Clean (USD)	Additional Energy Generated Due to Cleaning (kWh)	At Typical Avoided Energy Cost in CA ($0.13/kWh)	At California Solar Initiative Incentive Rate ($0.39/kWh)	At Spanish Feed-In Tariff (~$0.59/kWh)
2	$ 1,600	7,954	(565.92)	$ 1,502	$ 3,093
1	$ 800	2,738	(444.09)	$ 268	$ 815
0	$ -	0	-	$ -	$ -

4 MODEL VALIDATION

An important goal of the study conducted at the Los Angeles site was to validate the annual soiling losses predicted by the soiling model developed by Mitchell et al. As shown in Figure 1, the annual soiling loss predicted by the model for a system located in Los Angeles in a typical year is between 4.8 – 5.5%. The measured soiling loss in 2006 at our Los Angeles test site was 5.1%, showing excellent agreement with the model's predictions.

To further illustrate the predictive ability of the soiling rate/rainfall model, we used the model to predict the energy output of system B3 (the system that was not washed) during the summer months of 2006. Measured rainfall and measured irradiance and temperature data were used as inputs to the model. Figure 8 illustrates the fit of the rainfall model's predictions to actual measured data, and compares both of these quantities to the amount of energy predicted by a traditional constant-soiling model for the same time period. It is clear from this figure that the soiling rate/rainfall model has better predictive accuracy than a traditional constant-rate model.

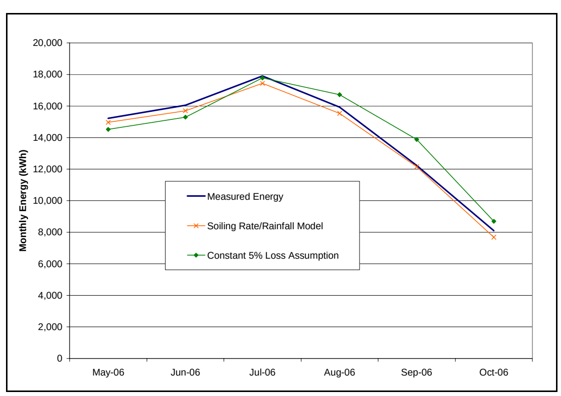

Figure 8: Measured energy compared to predicted energy

for System B3

5 CONCLUSION

As the performance loss due to soiling can be relatively large compared to other balance of system loss factors, it is important this effect be studied and accurately modeled in energy yield estimates. Our study in Los Angeles showed that annual system losses due to soiling are approximately 5%, in excellent agreement with the model developed by Mitchell, et al in 2006 [ref]. The economics of system cleaning will differ by region, environment and avoided energy cost. For our study in Southern California, cleaning becomes economical at an energy value of approximately $0.25/kWh. Because soiling losses vary so much by region and environment, it is also important that this effect is monitored and system operators and end customers are notified when soiling losses become excessive and when it becomes economical to clean a PV system.

6 REFERENCES

[1] A. Kimber, L. Mitchell, S. Nogradi, H. Wenger, Proceedings of the 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, USA; May 7-12, 2006