Effects of Dust on the Performance of PV Panels

Shaharin A. Sulaiman, Haizatul H. Hussain, Nik Siti H. Nik Leh, and Mohd S. I. Razali

Abstract—Accumulation of dust from the outdoor environment on the panels of solar photovoltaic (PV) system is natural. There were studies that showed that the accumulated dust can reduce the performance of solar panels, but the results were not clearly quantified. The objective of this research was to study the effects of dust accumulation on the performance of solar PV panels. Experiments were conducted using dust particles on solar panels with a constant-power light source, to determine the resulting electrical power generated and efficiency. It was found from the study that the accumulated dust on the surface of photovoltaic solar panel can reduce the system’s efficiency by up to 50%.

Keywords—Dust, Photovoltaic, Solar Energy.

I. INTRODUCTION

A Solar photovoltaic (PV) system uses solar cells to convert energy from sun radiation into electricity. The system is made up by one or more panels, a battery, a charge control and the load. Solar PV panels are normally mounted on roofs and wired into a building by an inverter, which converts the direct current energy received from solar panels into alternating current. There are many types of solar PV cells available, which are mainly monocrystalline silicon cells, multi crystalline silicon cells, thick film silicon, and amorphous silicon. The application of solar energy has become wider, with the solar photovoltaic industry’s combined global revenue of US$37 billion in 2008 [1].

In Malaysia, the government has recently been promoting the use of renewable energy due to several driving factors, such as the growing imports of oil and unutilized resources of renewable sources, increasing oil prices, and the environmental awareness. In the Tenth Malaysia Plan, it was reported that the nation attracted investments in solar power manufacturing that was worth RM9.8 billion or about 20% of investments in the electrical and electronics industries [2]. By 2015, the renewable energy capacity is expected to expand to 985 MW, which contributes 5.5% to Malaysia’s total electricity generation mix.

Located in the equatorial region, Malaysia has an average solar irradiation of 4500 kWh per square meter [3], and thus making it an ideal place for large scale solar power installations. Considering that the country gets an average of 4.5 to 8 hours of sunshine every day, there is huge potential for high solar power generation. At present, the number of solar PV applications in Malaysia is still low. It is generally restricted to rural electrification, street and garden lighting, and telecommunications. The first centralized solar power station was first built in year 2003, in a remote village, Kampung Denai in Rompin on the eastern coast of Peninsular Malaysia [3]. In a recent development, the Tenaga Nasional Bhd (TNB) who is Malaysia’s primary electrical power provider launched the development Malaysia’s first solar power plant in Putrajaya [4]. At an approximate cost of RM60 million or US$4 million per megawatt, the project signifies a major step in harnessing the use of renewable energy in the country. The project would be expected to enable the operator to understand the system well before embarking into development of plants of bigger scale.

A drop in the efficiency of a solar PV panel throughout its life cycle is not desired, since the capital cost for the system is quite high. PV cells can normally last for about 25 years, and it takes approximately up to six years [5] for the solar PV module to generate the equivalent amount of energy consumed in its manufacturing processes. One of the contributing factors in the drop of efficiency of solar PV panels in Malaysia as well as in other country is the accumulated dust on the panel. The nature of the problem may vary by geographical locations.

Hottel and Woertz [6] were amongst the pioneers investigating the impact of dust on solar systems. They recorded a maximum degradation in collector performance of 4.7%, with an average loss in incident solar radiation being less than 1%. In a study by Salim et al. [7] into dust accumulation on a solar-village PV system near Riyadh indicated a 32% reduction in performance after eight months. Wakim [8] indicated a 32% reduction in PV power by 17% due to sand accumulation on panels in Kuwait city after six days. Furthermore the study also indicated that the influence of dust on PV performance would be higher in spring and summer than in autumn and winter. An experiment to investigate the effect of aeolian dust deposition on photovoltaic solar cells by Dirk Goosen et. al [9] showed that the deposition of fine aeolian dust particles on the glazing of PV cells significantly affected the performance of such cells. This experiment was conducted to investigate the effect of wind velocity and airborne dust concentration on the drop of PV cell performance caused by dust accumulation.
Google, one of the world’s well-known organizations in the information technology studied the effects of dirt on solar panels of a 1.6 MW solar installation in its Mountain View headquarters in California [10]. The company made a comparison on two different sets of solar panels in Google campus – the flat ones in carports and the tilted ones on roofs. Theoretically, dirt accumulates on top of the flat panels, whereas rain washes away most dirt on the tilted ones and leaves some accumulation in the corners. The Google crew cleaned them up as part of this study, 15 months after the installation of the panels. For the flat panels, the cleaning resulted in doubling of the energy output overnight. However, for the tilted panels, the difference was found to be relatively small. In a different study on the effects of dust on solar PV panel in Palo Alto, California [11], it was reported that the dirt on solar PV panels caused a 2% of current reduction relative to that for clean panels. Like the other reports, these two studies in California did not quantify the amount of dust involved.

In an experiment in Roorkee, India, Garg [12] discovered that dust accumulation on a glass plate tilted at 45° would reduce the transmittance by an average of 8% after an exposure period of 10 days. In a work by Sayigh [13] in Kuwait, it was observed that about 2.5 g/m²/day of dust were collected between April and June. Further investigation [14] on the effect of dust accumulation on the tilted glass plates revealed a reduction in plate-transmittance ranging from 64% to 17%, for tilt angles ranging from 0° to 60° respectively after 38 days of exposure. A reduction of 30% in useful energy gain was observed by the horizontal collector after three days of dust accumulation. In another study that included investigations of the physical properties and deposition density on the performance of solar PV panels by El-Shobokshy and Hussein [15], the artificial dust which included limestone, cement and carbon particulates were used. They used halogen lamps to represent the source of radiation energy. It was revealed in the study that cement particles (at 73 g/m²) would result in the most significant drop in the PV short-circuit voltage; i.e. by 80%. Interestingly, it was found that the smaller the particle size for a fixed deposition density, the greater would be the reduction in solar intensity received by the solar PV panels. This was probably due to the greater ability of finer particles to minimize inter-particle gaps and thus obscuring the light path more than that for larger particles.

In this paper, the influence of dirt accumulation on the efficiency of solar PV panels is assessed by using artificial materials. A constant light radiation condition is used by mean of spotlight to overcome the variation that may be experienced under the sunlight.

II. EXPERIMENT APPARATUS AND SETUP

Shown in Figure 1 is schematic of the experiment rig. Basically the system comprised a solar photovoltaic panel (rated 50 W), as shown in Figure 2, a set of spotlight and the electrical circuit system. The solar panel module was made up of silicon mono-crystal cells; each cell had an area of 10 cm². The dimensions of the panel were 1004 mm by 448 mm by 43 mm. The system was installed in an indoor lab and the radiation energy was delivered by the spotlight system, each rated at 500W. The number of spotlights and their positions could be varied depending on the requirements of experiments. To measure irradiation on the solar panel, a HD2302 Delta OHM photo-radiometer was used. For the measurements of voltage and current, Sanwa YX360TRF analogue multimeters were used in the arrangement as illustrated in Figure 1. The system’s load was simulated by using different resistors.

Experiments were performed by applying artificial dusts on a layer of plastic sheet, prior to placing the set onto the solar PV panel. Tests were conducted also with the clean plastic sheet and with bare panel in order to quantify the effects of dust on the performance of the PV panel. In each condition, the distance between the spotlight and solar PV panel was varied in order to develop the current-voltage characteristics of the panel. The decision on the appropriate number of spotlights is described in the next section.

![Fig. 1 Schematic of the system](image-url)
In this project, two types of artificial dust; i.e. dried mud and talcum powder, were used instead of real dust to represent the dust accumulation. The use of natural dust accumulation was avoided because it might not be well distributed on the surface of solar PV panel, since it would be exposed naturally to the environment and the dust settlement could be subjected to the wind effect. Such non-uniformity might be neutral but it would complicate study of the fundamental aspect of the dust effect.

In order to quantify the thickness of the dust layer, a clear plastic sheet was placed on the solar panel for surface protection. The artificial dust was prepared by distributing the particles evenly on the plastic sheet. In order to measure the thickness of the dust layer, a tiny portion of the plastic sheet (with dust on it) was cut and was sent to the laboratory for measurement using the Scanning Electron Microscope (SEM). All experiments were executed by measuring the output voltage and current produced by solar PV. Clean solar panel without plastic covering its surface was chosen as true control. The experiment is then continued using three different plastic sheets to represent different conditions of dust accumulation on the surface of solar panel.

Shown in Figures 3 and 4 are images of the cross-section of the artificial dust layers and plastic sheets obtained using the Scanning Electron Microscope at 200× magnification. The thickness of the clear plastic sheet was 28 µm as measured in both figures. The average thickness of the dry mud layer is found to be about 41 µm, and about 103 µm for the talcum powder layer. Although the dust was spread evenly on the plastic sheet, the thickness seemed to be varied when examined through the SEM. Therefore, approximation was made in judging the average thickness of the dust layers.

III. IDENTIFICATION OF OPTIMUM HEIGHT OF LAMPS

Shown in Figure 5 is the variation of the irradiation measured on the panel with distance between the light source and the surface of PV solar panel, with the use of only one spotlight. Three measurements were taken at different positions on the panel to check the distribution of irradiation. Reading 1 was taken at the centre of solar PV panel, and Reading 2 and Reading 3 were obtained 5 cm and 10 cm away from the centre, respectively.
In Figure 5 the radiation intensity from the light is shown to be the highest when the distance from PV solar cell is the smallest, and vice versa. The results are shown to be repeatable but there is a relatively significant scatter in the results when the distance between the lamp and the panel is the nearest.

The same experiments were repeated but with the use of two spotlights and the results are shown in Figure 6. It is shown from the figure that the results are highly repeatable when two spotlights are used in comparison to that using only one spotlight. Thus, it implied that the use of two spotlights would be preferred in the study, as it would be able to resemble close to the real condition in which the sun’s radiation intensity would be well distributed over a small area (i.e. the panel). In general the trend of variation in results of Figure 7 is similar to that in Figure 6; i.e. irradiation is inversely proportional with distance between the light source and the panel. Fig. 6 reveals a pattern of incoming solar energy at different distances from the sun. The larger scatter among the measurements in Figure 5 relative to that in Figure 7 shows that the resulting irradiation on the solar panel by using one spotlight was not well distributed, and hence the use of two spotlights would be a better option. Therefore, the experiments were using two spotlights as the source of radiation heat. The distances between the lamps and the panel for the experiments were set to be 240 mm, 280 mm and 340 mm, which correlated to irradiation values of 340 W/m², 301 W/m², and 255 W/m², respectively.

IV. RESULTS AND DISCUSSIONS

A. Voltage –Current Characteristics

Shown in Figures 7 to 9 are the current-voltage or I-V curves for solar PV panels in all conditions: clear plastic sheet, plastic coated with mud, plastic coated with talcum powder, and solar PV without any plastic sheet for different irradiation values. The solar PV panel produced a maximum power of 4.25 W as recorded for the clear plastic sheet and solar PV panel without plastic. The maximum voltage measured was 18 V.

For irradiation of 255 W/m² and 301 W/m², the curve for all four conditions are quite close to each other, in which the differences among them are not significant. However when the experiment was conducted at irradiation of 340 W/m², the curve for plastic coated with talcum powder seems to have a significant difference compared to the other three conditions. This was probably due to the effects of dust accumulation on it which was far more effective in obstructing the light from hit the surface of the solar PV panel.

In general the trend of current-voltage characteristics is shown to be similar with that of typical solar panels. Since the area under the curve would represent the electrical power of the solar PV system, it can be summarized from the graphs that the highest power could be produced when the panel is not covered by layer of dust or plastic. With the introduction of dusts, the area within the curve becomes smaller, implying the reduction in energy generated. The peak power, which is normally represented by the top corner point of the curve, also shows the same trend of reduction due to the presence of dust.
The effect of dust on the panel is quantified by tabulating the peak powers of the solar PV panel under each experiment condition. Shown in Table I are the values of peak powers for different conditions of panel’s surface and irradiation value. The peak powers were obtained from calculations using the measured values of current and voltages.

### Table I: Peak power for different conditions on the PV panel

<table>
<thead>
<tr>
<th>Condition</th>
<th>Peak power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>255 W/m</td>
</tr>
<tr>
<td>No plastic</td>
<td>4.25</td>
</tr>
<tr>
<td>Clean plastic</td>
<td>4.25</td>
</tr>
<tr>
<td>Mud</td>
<td>3.48</td>
</tr>
<tr>
<td>Talcum</td>
<td>3.55</td>
</tr>
</tbody>
</table>

It is shown in Table I that the highest peak power occurred when the panel was not covered. The clean plastic reduces the peak power slightly except for the case of 340 W/m of irradiation and further investigation would be suggested in the future. The cause for this is not well understood. If the results using irradiation of 340 W/m were to be excluded, the reduction caused by the mud layer was found to be as high as 18.1%; i.e. under the lowest irradiation. Talcum powder exhibited almost the same reduction; i.e. a maximum of 16.5%. In general the trend is the effect of the presence of dust is less significant under high irradiation condition. The lowest reduction was 3.6%, for mud at irradiation level of 340 W/m.

To determine efficiency of the solar panel, the equation is given by [16]:

\[ \eta = \frac{V_i P_i}{P_s A} \times 100\% \]  

where \( I_p \) is the electrical current produced by the solar PV panel, \( V_s \) is the voltage of the electricity produced, \( P_s \) is the power of the incident solar radiation (W/m²), and \( A \) is the exposed area of the solar cell. It must be noted though that Eqn. (1) is intended for use under standard test condition; i.e. under a temperature of 25°C and an irradiance of 1000 W/m² with an air mass 1.5 (AM1.5) spectrum. In the present work, the required irradiance was not met, but the calculation of efficiency was meant as an indicator for comparison between the different conditions of solar panel surface.

The highest calculated efficiency for the clean plastic is 4.82%, plastic coated with mud is observed to be 3.95%, plastic coated with talcum powder is observed to be 4.03%, and for solar PV panel without plastic is observed to be 4.82%. This clearly shows that clean plastic and solar PV panel without plastic gives the highest efficiency due to the absence of dust on its surface.

**V. Conclusions**

The effect of presence of dust was studied using artificial dust (mud and talcum) under a constant irradiance conducted in an indoor lab. Dust has an effect on the performance of solar PV panel. The reduction in the peak power generated can be up to 18%. It was also shown that under greater irradiation, the effect of dust became slightly reduced but not negligible. In the study, it was also shown that the differences between the results obtained by using mud and talcum were generally small; i.e. about 6%. Hence, in practice, dust must be removed from the surface of solar PV panel in order to ensure highest performance, given the fact that it is still a costly form of energy source and the short lifespan it has.

**Acknowledgment**

The authors would like to express their deepest appreciation to Universiti Teknologi PETRONAS for their technical assistance and support in this project.

**References**


Soiling Losses for Solar Photovoltaic Systems in California

Felipe A Mejia, Jan Kleissl

Keywords: Soiling, PV Performance

Center for Renewable Resources and Integration, Department of Mechanical and Aerospace Engineering, University of California, San Diego 9500 Gilman Dr., La Jolla, CA 92093, USA

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°) 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 (\eta_r) for the solar panels was calculated, controlling for the effects of temperature \eta_T and inverter \eta_{AC} efficiency as follows:

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

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

where \(G_{SAW}\) 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 \(\eta_T = 1 - \alpha (T_{cell} - 25^\circ C)\) 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, \(\eta\) was then normalized by its average for the year to obtain a relative performance \(\eta_r\).

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 $\eta_r$ for each site over the course of the year. At 36 sites $\eta_r$ 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 $\eta_r$ during the summer, suggesting soiling, but $\eta_r$ 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 $\eta_r$ for the week before a rain event ($\eta_b$) and for the week after a rain event ($\eta_a$). 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 $\eta_r$ and daily rainfall for a 554 kW$_{ec}$ 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 ($\eta_b$ in red) and after ($\eta_a$ 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 ($\eta_1$ in blue) and the last week of the drought ($\eta_f$ 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 $\eta_s$ and the week before the next rain event $\eta_f$ 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° 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° contains 12 sites, 102 sites have tilts from 6° to 19° and 88 sites have tilts equal to or greater than 20°.

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.

Acknowledgements

This work was supported by the California Solar Initiative RD&D program. We are grateful to Stephan Barsun, Itron for helpful comments and provision of literature. SolarAnywhere data for all of California was provided by Clean Power Research (Thomas Hoff and Skip Dise).


### Tables

#### Table 1. Soiling losses stratified by tilt angle.

<table>
<thead>
<tr>
<th>Tilt Angle</th>
<th>Number of Sites</th>
<th>Mean Soiling Losses [10^-4 day^-1]</th>
<th>Fraction of sites with soiling &gt; 0.1/day [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt &lt; 5°</td>
<td>12</td>
<td>-18.0</td>
<td>50</td>
</tr>
<tr>
<td>5° &lt; Tilt &lt; 19°</td>
<td>90</td>
<td>-5.2</td>
<td>24.4</td>
</tr>
<tr>
<td>Tilt &gt; 20°</td>
<td>84</td>
<td>-5.3</td>
<td>23.8</td>
</tr>
</tbody>
</table>

#### Table 2. Soiling losses stratified by geographical region.

<table>
<thead>
<tr>
<th>Geographical Region</th>
<th>Number of Sites</th>
<th>Mean Soiling Losses [10^-4 day^-1]</th>
<th>Fraction of sites with soiling &gt; 0.1%/day [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Francisco Bay</td>
<td>47</td>
<td>-4.8</td>
<td>12.8</td>
</tr>
<tr>
<td>Central Valley</td>
<td>29</td>
<td>-5.8</td>
<td>24.1</td>
</tr>
<tr>
<td>SCE</td>
<td>75</td>
<td>-8.3</td>
<td>41.3</td>
</tr>
<tr>
<td>SDG&amp;E</td>
<td>35</td>
<td>-2.7</td>
<td>11.4</td>
</tr>
</tbody>
</table>
Photovoltaic Modules: Effect of Tilt Angle on Soiling

by

Jose Cano

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science in Technology

Approved July 2011 by the
Graduate Supervisory Committee:

Govindasamy Tamizhmani, Chair
Arunachalanadar Madakannan
Narciso Macia

ARIZONA STATE UNIVERSITY
August 2011
ABSTRACT

Photovoltaic (PV) systems are one of the next generation’s renewable energy sources for our world energy demand. PV modules are highly reliable. However, in polluted environments, over time, they will collect grime and dust. There are also limited field data studies about soiling losses on PV modules. The study showed how important it is to investigate the effect of tilt angle on soiling.

The study includes two sets of mini-modules. Each set has 9 PV modules tilted at 0, 5, 10, 15, 20, 23, 30, 33 and 40°. The first set called "Cleaned" was cleaned every other day. The second set called "Soiled" was never cleaned after the first day. The short circuit current, a measure of irradiance, and module temperature was monitored and recorded every two minutes over three months (January-March 2011). The data were analyzed to investigate the effect of tilt angle on daily and monthly soiling, and hence transmitted solar insolation and energy production by PV modules.

The study shows that during the period of January through March 2011 there was an average loss due to soiling of approximately 2.02% for 0° tilt angle. Modules at tilt angles 23° and 33° also have some insolation losses but do not come close to the module at 0° tilt angle. Tilt angle 23° has approximately 1.05% monthly insolation loss, and 33° tilt angle has an insolation loss of approximately 0.96%. The soiling effect is present at any tilt angle, but the magnitude is evident: the flatter the solar module is placed the more energy it will lose.
ACKNOWLEDGMENTS

I would like to thank Dr. Govindasamy Tamizhmani for sharing his knowledge and experiences in the photovoltaic (PV) technology industry. He has shaped my understanding and my future in expanding my career in PV technology. I would also like to thank Dr. Madakannan and Dr. Macia for their valuable recommendations.

I would like to thank my colleagues in the Department of Engineering Technology, and the Arizona State University Photovoltaic Reliability Laboratory for their kind help to finish this work successfully.

Finally, words alone cannot express the thanks I owe to my family for their support and encouragement. Without them, it would never have been possible.
TABLE OF CONTENTS

| LIST OF TABLES | .......................................................................................................... vi |
| LIST OF FIGURES | ......................................................................................................... vii |

CHAPTER

1 INTRODUCTION ........................................................................................................... 1
   1.1 Background ....................................................................................................... 1
   1.2 Statement of Problem ........................................................................................ 2
   1.3 Scope .................................................................................................................. 2
   1.4 Assumptions and Limitations .......................................................................... 3

2 LITERATURE REVIEW ............................................................................................. 4
   2.1 Analysis of Previous Studies ........................................................................... 4
   2.2 Summary and Findings ..................................................................................... 16
   2.3 Incident Angle .................................................................................................. 17
   2.4 Solar Energy ................................................................................................. 18
   2.5 Effect of Temperature Coefficients .............................................................. 18
   2.6 Irradiance Calculation ....................................................................................... 21

3 METHODOLOGY ........................................................................................................ 22
   3.1 Effect of Tilt Angle on Soiling ....................................................................... 22
   3.2 System Installation ........................................................................................... 23
   3.3 Photovoltaic Modules ..................................................................................... 24
   3.4 Photovoltaic Module Calibrations ................................................................. 27
   3.5 Data Acquisition System ................................................................................. 31
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>RESULTS AND DISCUSSIONS ........................................................ 34</td>
</tr>
<tr>
<td></td>
<td>4.1 Soiling Modeling for Tilt Angle ................................................. 34</td>
</tr>
<tr>
<td></td>
<td>4.2 Soiling Based on Experimental Results ..................................... 34</td>
</tr>
<tr>
<td></td>
<td>4.3 Validation of Experimental Data ............................................... 47</td>
</tr>
<tr>
<td>5</td>
<td>CONCLUSIONS AND RECOMMENDATIONS ............................................. 48</td>
</tr>
<tr>
<td></td>
<td>5.1 Conclusions ................................................................................. 48</td>
</tr>
<tr>
<td></td>
<td>5.2 Recommendations ...................................................................... 48</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>........................................................................................................ 49</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>A Calibration of Irradiance Mesh Screens ........................................... 51</td>
</tr>
<tr>
<td></td>
<td>B Linearity Check of Irradiance Sensors ............................................ 53</td>
</tr>
<tr>
<td></td>
<td>C Calibrated Short Circuit Values and Temperature Coefficients for Solar PV Modules ........................................................ 56</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.</td>
<td>Daily Average Insolation Losses Before Rain and After Rain for Week Seven</td>
<td>38</td>
</tr>
<tr>
<td>4.2.</td>
<td>January to March Insolation Values and Losses for Clean and Unclean Solar PV Modules</td>
<td>40</td>
</tr>
<tr>
<td>4.3.</td>
<td>Insolation Percentage Losses for February 11, 2011</td>
<td>44</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>2.1</td>
<td>How to Calculate the Radiation Incident on a Tilted Surface</td>
<td>17</td>
</tr>
<tr>
<td>2.2</td>
<td>Effect of Temperature on PV Cell Using Example Coefficients</td>
<td>20</td>
</tr>
<tr>
<td>3.1</td>
<td>Polycrystalline Silicon Solar Cell Sensor</td>
<td>24</td>
</tr>
<tr>
<td>3.2</td>
<td>Tilt Angles of Modules</td>
<td>26</td>
</tr>
<tr>
<td>3.3</td>
<td>Modules Right Before Screen Mesh and Modules During Linearity Calibration</td>
<td>30</td>
</tr>
<tr>
<td>3.4</td>
<td>System Array in the Field</td>
<td>31</td>
</tr>
<tr>
<td>3.5</td>
<td>Data logger CR1000, Multiplexer AM16/32B and AM416 Relay Multiplexer</td>
<td>32</td>
</tr>
<tr>
<td>3.6</td>
<td>Screenshot of PC200W</td>
<td>33</td>
</tr>
<tr>
<td>4.1</td>
<td>Insolation Losses for Each Tilt Angle from January through March</td>
<td>35</td>
</tr>
<tr>
<td>4.2</td>
<td>Average Daily Insolation Losses for 0° Tilt Angle and Total Rainfall in Millimeters</td>
<td>36</td>
</tr>
<tr>
<td>4.3</td>
<td>Average Daily Insolation Losses for 23° Tilt Angle and Total Rainfall in Millimeters</td>
<td>38</td>
</tr>
<tr>
<td>4.4</td>
<td>Average Daily Insolation Losses for 33° Tilt Angle and Total Rainfall in Millimeters</td>
<td>39</td>
</tr>
<tr>
<td>4.5</td>
<td>Average Daily Insolation Values for Clean and Unclean Solar Module for Three Months for All Tilt Angles</td>
<td>40</td>
</tr>
<tr>
<td>4.6</td>
<td>Weekly Insolation Percentage Losses for January through March, 2011</td>
<td>41</td>
</tr>
</tbody>
</table>
4.7. Soiling Comparison on February 11, 2011 for Clean and Unclean Modules at 0°, 5°, 10° and 23° Tilt Angles ........................................ 43

4.8. Cleaned and Soiled Solar PV Module for 23° Tilt Angle............... 45

4.9. Soiling Comparison on February 19th, 2011 Before and After Rainfall........................................................................................................ 46

4.10. NREL versus. PRL Horizontal Plate........................................... 47
CHAPTER 1
INTRODUCTION

1.1 Background

Field data for energy losses due to soiling are limited in today’s photovoltaic (PV) industry. This study aims to provide a better understanding of the extent at which tilt angle affects the soiling, and hence the performance, of PV modules. To better understand the effect of tilt angle on soiling, one has to know how it affects the short circuit current of the PV modules as it is directly proportional to the irradiance reaching the solar cells. The incident irradiance on PV cells inside a PV module and the operating temperature of PV cells primarily dictate the power output of module. On a dual axis tracker, when module surface and the incident light rays are perpendicular to each other, the power output will be the highest [1]. However, on a fixed tilt, the power output will be dictated by sun’s position and tilt angle.

Also, the radiation received by cells inside the PV module is lower than radiation arriving to the module surface. The main causes of this energy loss are dirt accumulation on the surface of the modules and reflection and absorption losses by the materials covering the cells. These reflection losses depend on the radiance incident angle; thus, they are normally referred to as angle of incidence (AOI) losses [2].

The performance of PV cells depends on many operating conditions. In this study the parameters that are being investigated are irradiance and soiling at different tilt angles. These are some parameters the industry uses to predict
energy output for PV modules. The data acquisition system collected data every two minutes between January and March 2011. This study is primarily focused on obtaining the insolation input and hence the energy output of a specific tilt angle when it is clean and unclean. The experimental set up is designed and developed for measuring the temperature and short circuit current (in the form of voltage drop across a shunt resistor). The data obtained by measuring these two parameters is translated into giving the transmitted irradiance at each different tilt angle. Thus, the transmitted irradiance will give us estimation on the energy loss due to soiling.

1.2 Statement of Problem

The main objective of this study is to conduct an experiment quantifying the relationship between tilt angle and soiling. The experiment recorded data over a period of three months showing the effect of dirt on several modules assembled on an open rack configuration. This data was compared with other identical modules placed also in an open rack configuration that is regularly cleaned. A comparison analysis was used to conclude what was the effect of tilt angle on soiling [3].

1.3 Scope

The solar irradiance reaching PV cells of fixed tilt modules depends on the tilt angle of the modules and the extent of soiling on the surface of the modules. The soiling effect increases as the tilt angle decreases. The extent of soiling dictates overall energy production of the modules on a daily, monthly, seasonal
and annual basis. The primary objective of this project is to quantitatively identify the effect of tilt angle on soiling of PV modules.

The scope of the work includes:

- Confirming short circuit current linearity with irradiance for each 18 mini polycrystalline silicon module (1 Watt) to IEC 60904-10 standard [4].
- Designing, constructing and installing an open rack steel frame to mount 18 mini solar PV modules so as it could be mounted for different tilt angles.
- Collecting and monitoring temperature ($T_{\text{cell}}$) and short circuit current using a shunt resistor across each module to measure irradiance in the form of voltage ($V_{\text{module}}$) data for 18 modules with various tilt angles (tilt angles: 0°, 5°, 10°, 15°, 20°, 23°, 30°, 33°, 40°) and for a time period (January to March 2011).
- Analyzing and quantifying data for the estimation of insolation/energy losses for each tilt angle.

1.4 Assumptions and Limitations

The test station was set up at the Arizona State University Polytechnic campus in Mesa, Arizona. Since the outdoor soiling results were obtained only at one location, Mesa, Arizona, they may or may not be applicable to other climatic conditions.
CHAPTER 2
LITERATURE REVIEW

2.1 Analysis of Previous Studies

The performance of the module is affected by many factors. The factors that can affect the performance include: tilt angle, irradiance, soiling, module temperature and many more [5]. That is why analytical models are created to better understand how these issues affect the PV module’s performance. There are many existing models that show how these parameters can be used to predict the PV’s cell performance, but for this thesis only the effect of soiling is examined. Soiling is a term used to describe the accumulation of dirt on solar panels that reduces the amount of sunlight reaching solar cells. It is often a problem in the areas where it is not raining for months in a row. This has a cascading effect on performance, from the reduction of sunlight to causing reduced energy absorption by solar cells. This can cause the whole system to work harder and consequently reduces energy output.

Garcia, Marroyo, Lorenzo and Perez conducted research on irradiance incidence angle losses and dirt energy losses in 2005 measured at a plant located in the North of Spain [6]. The plant has 400 single vertical-axis trackers and 45° tilted modules. Crops mainly surround it, but at a distance of 1 km, there is a road with regular traffic flow. The main soiling factors that influenced this study were dust and bird droppings. The study methodology was based on comparison between irradiance measured by two horizontal pyranometers and irradiance measured by three calibrated cells located on separate trackers [6]. In the same
way incidence angle and dirt losses of fixed horizontal plant were determined on the basis of three horizontally placed cells’ measurements. The effect of dirt on these types of installations was compared and analyzed.

There were six calibrated cells placed along the plant, which were using the same technology as the PV modules’ cells. They were installed on three trackers. Three of them were placed at the same plane as the modules, the rest were positioned horizontally. Measurements of temperature and short-circuit current allowed to calculate irradiance incidence. The dirt accumulated on the cells is considered the same as the one on PV modules, but the bird droppings were cleaned, as their influence research was not the goal of the study. Diffuse and global horizontal radiation was measured with two Kipp & Zonen CM11 pyranometers that were cleaned on regular basis.

Daily optical energy losses were calculated between February 2005 and May 2006. They varied according to seasonal peculiarities. In this area it usually rains in autumn and spring. In case of tracking surfaces the losses range was between 1 and 8%, and in the case of horizontal surfaces – from 8 to 22%. It was defined that rain contributed to the cells cleaning only when it reached a value of 4-5 mm [6]. The biggest losses were observed in the late winter, when rainfall had the lowest level and was the least intense. In summer, the highest levels of losses were registered on dry days. Differences between the horizontal and tracking surfaces were clearly observed. In the first case, they were intense and did not vary considerably throughout the year. In tracking surfaces, monthly
optical soiling losses varied between 2 and 6% and were more influenced by the rainfall.

Optical losses due to AOI were constantly observed round the year, being practically permanent all the time for the tracking surfaces – about 1%. For horizontal samples, these losses were 2 to 3% in summer and 8% in winter [6]. Total optical energy losses for tracking surfaces were 3.8% (1% due to AOI, the rest because of dirt) and for horizontal – 11.9% (5% due to AOI, the rest because of dirt). Thus, in this study it was found that horizontal surfaces were more affected by dirt, which is why their rate of losses was considerably higher than in the case of tracking position.

In the study by Kimber, Mitchell, Nogradi and Wenger [7] effect of soiling was analyzed for large grid-connected PV systems in California and US Southwest region. These regions were chosen, as rainfall there is limited for several months in the year and is practically absent in the peak solar months of summer, which allows investigating the effect considerable accumulations of dirt have on the systems.

For this study, 250 PV systems were daily monitored in Berkley, CA headquarters. The main source of information was 15-minute remote monitored data gathered from these systems. In the study, different levels of losses were observed in accordance with the rainfall and duration of dry season. The purpose of the study was development of a model that approximates the soiling pattern observed in measured performance data to improve the simulations accuracy [7].
Decline in the systems performance throughout the dry season was practically linear, although systems, while being put in similar conditions, did not show the same performance recovery and degradation patterns. It was discovered that the activity in system’s immediate environment directly influences these patterns. Thus, it was assumed that the soiling effects on PV systems performance could be predicted by application of a linear model of systems’ performance decreasing over time between rainfall events. Different rates of system performance decline would be applicable for different locations.

In order to check the validity of linear approach to soiling losses approximation, linear regression was used for performance data gathered at 10 systems in 2005 dry season, which was a preliminary study [7]. The systems were located in different parts of the world, so the results offer a cross-section of system locations and soiling. Analysis of the results showed that a half of the study samples showed “grace period” after the period were soiling was practically negligible (the last rain in spring) and within the periods when soiling rates were slower than those of the dry seasons’ last months. Still, the fact that another half of the samples did not have such period shows non-uniformity of behavior. Another non-uniformity was observed in the unpredictable nature of systems performance after light autumn or late-summer rainfall. Such results of the preliminary study showed the necessity of further research of the rain amount necessary to clean the systems.

The main study was conducted on 250 systems based on the 2005-year data. Each of the systems was assigned to local environment type and
geographical region. For each region there was defined the dry season, which lasted from the last rainfall of the rainy season to the first rainfall afterwards. Regions, where rainfall occurred not less than once a month, showed no particular energy losses due to soiling. They included Hawaii, Germany, Northeast, Midwest, Mid-Atlantic and Southeast [7].

California and Desert Southwest regions showed gradual decline in performance throughout the dry season. There were 46 systems in this region with $R^2$ value of more than 0.7 that were analyzed in particular. The amount of rainfall necessary to clean the systems was found to be higher than in some previous studies, where it was of 5 mm [6]. For systems in Northern California, only rainfall of 20 mm was enough to clean them and increase the systems performance by 40%. Still, after analysis of all the systems under consideration it was discovered that there is no definite answer as to the amount of rainfall necessary for all the systems to be cleaned. The indicator varied from region to region. In addition, it was also observed that light rain can even decrease the efficiency of systems.

Based on study results a model was derived of PV system performance degradation related to soiling. Field conditions were approximated in the model by eliminating losses related to soiling during rainy season and increasing them in the dry period. There are three major elements in the model: cleaning threshold (amount of rain necessary to clean the system); Grace Period length (number of days after the last rain when a system is clean); soiling rate (factor describing performance degradation rate due to soiling). In order to validate this model, its
logic was incorporated in the code of PVGrid, PowerLight’s solar electric system simulation program [7]. Seven systems were used in the validation process. The model was used for prediction of annual soiling losses for a generic PV system in each region of the study. The results showed that the average annual loss varied from 1.5% to 6.2%, while in the last month of the dry season this indicator rose to 27%.

As a result of the study, a new model defining energy losses level due to soiling was empirically derived and incorporated in a simulation program utilizing typical rainfall data and TMY2 data files. It was discovered that PV system’s efficiency decreases by 0.2% daily within the dry season. In this way, annual loss of 1.5-6.2% energy was calculated in dependence on the climate.

Study conducted by Levinson et al. [8] showed soiling and cleaning effect on solar heat gain and reflectance of light-colored roofing membrane. White roof reduces cooling power demand in case of a conditioned building and increases comfort in summer for unconditioned buildings. Still, high level of initial solar reflectance is affected by accumulation of biomass, soot and dust. The study was aimed at investigation of soiling and cleaning effects on solar absorptances and solar spectral reflectances of 15 initially light-gray or white PVC membranes from roofs in good condition from eight US states.

Small parts of each membrane were extracted from each unsoiled and heavily soiled sample. Spectral reflectance was measured after each of the processes of wiping, rinsing, washing and bleaching, which simulated natural and artificial cleansing mechanisms. There were the following soil layers spotted:
tightly bound material that was removed by washing or rinsing; loosely bound material that was wiped off; biological growth that was cleaned only by bleach [8].

Organic and black carbons were two absorbing contaminants on membranes. Wiping was effective for black carbon cleaning. Washing and/or rinsing removed practically all the other soiling, except for thin layers of organic carbon and biomass. In order to clean the remaining layers, bleach turned out to be effective. Still, the results varied for different layer thicknesses. It was discovered that solar reflectance indicator for light-colored roof can be decreased by 50% if it was sickly coiled with black carbon and/or biomass to the extent when it turned black or brown.

Solar absorptance ratio, which is a proper indicator of soiling effect, is typically 0.2 for unsoiled roof. In case of heavy soiling, it can increase threefold, increasing solar gain in the same way. What is peculiar about this ratio, is that even after cleaning the membranes, the solar gain was 90% higher than before soiling [8]. At the same time, this indicator is still much lower than the one of unsoiled black membrane.

As a result, it was observed that organic carbon, and especially black carbon, considerably reduced solar spectral reflectances of 15 roofs under consideration. The ratio of solar reflectance to unsoiled indicator was from 0.41 to 0.89 for soiled samples, 0.74-0.98 for rinsed; 0.53 to 0.95 for wiped; 0.94-1.02 for bleached and 0.79-1.00 for washed. Solar absorptance ratios was 1.4-3.5 for
soiled samples; 1.0-1.9 for washed; 1.0-2.0 for rinsed; 1.1-3.1 for wiped; 0.9-1.3 for bleached [8].

The research conducted by Massi Pavan, Mellit and De Pieri [9] investigated the effect of soiling on production of energy for large-scale PV plants. There were two PV plants considered in this study that are located in the southern Italy. Tilt angle at the plants is 25°, while the shading angle is 20°. The plants are made with Q.Cells multi-crystalline silicon QC-C04 modules. The monitoring system used in the study consisted of radiation sensor, two temperature sensors, Controller Area Network Bus interface, acquisition board in each DC board, data logger and server for dataset storage.

For each plant two datasets of climate and electrical data were collected – one for soiled modules and one for clean. For cleaning of the first plant’s modules squirting with under pressure-distilled water and brushing was used, while for the second plant only squirting. There were two acquisition periods – from June 21 to August 15, 2010, and from September 1 to October 21, 2010 [9].

There were three performance parameters used for assessing operation of PV systems, according to IEC standard 61724: reference yield, system yield and performance ratio. Limitation for the purposes of this study is that these parameters are affected by weather. In order to make the results weather-independent, there were other parameters for characterization of performance proposed: PVUSA rating method, SANDIA array performance model, generic polynomial regression model. The latter of the methods was chosen for determining of the powers for soiled and unsoiled systems. Two datasets for
every plant are related to eight-week period when the modules were soiled and seven weeks after cleaning.

As a result, it was discovered that cleanness of the PV modules secured average benefits of 6.9% for the first plant and 1.1% for the second one. Differences between the results for plants can be explained by the following facts: the first site was sandier than the second one, so the effect of pollution was greater there; different cleaning methods for the plants were applied [9]. Correlation coefficients between powers predicted by the regression model and the measured ones showed high efficiency of the selected model.

The results show that effect of soiling depends greatly on the type of soil and the washing technique applied. In case of the first plant, losses due to soiling were 6.9%, while in the second case – only 1.1%. Economic index calculated for each plant showed the efficiency of cleaning and considerable amount of money that can be saved [9].

Qasem, Betts, and Gottschalg [3] argue that increasing tilt angle can mitigate the effect of dust accumulation for configurations of three Cadmium-Telluride PV thin cell modules, but using tilt to mitigate dust accumulation creates increased risks of generating hot spots on cells as tilt becomes oriented toward a horizontal position. This finding is the result of a simulation rather than real-world environmental testing. Simulations were conducted using the circuit analysis software PSPICE and three-dimensional models were created to facilitate hot spot study. The models focused on the effects of sand dust, which can affect electricity production through both the scattering and absorbing of light. [3]
Utilizing optimal vertical tilt creates accumulations of dust and sand particles on the lower third of cells in the simulation, and this accumulation creates a vulnerability to the creation of hot spots. Loss of power in horizontal three cell configurations is significant. The simulation shows a power loss of 66.7% for a voltage-limiting cell and 66.3% for a current limiting cell in comparison to 42.2% and 44.1% respectively for a vertical cell configuration [3].

Hammond, Srinivasan, Harris, Whitfield, and Wohlgemuth [10] presented real-world results from studying various configurations of tilt and soiling in 1997. The study examined soiling effects from three independent applications utilizing time periods of sixteen months to five years. The general findings include that bird droppings create far greater power loss than soiling, in part because rainfall does not mitigate the loss of power attributed to droppings.

With all modules tested tilting normal to the sun, soiling losses generally remain fixed at approximately 2.3%. As the angle of incidence increases to 56 degrees soiling effects are significantly increased, reaching 7.7% at 56 degrees. The studies also show that soiling effects, during the first year of operating, are generally eliminated during rainfall when greater than five millimeters. The remediating effect of rainfall remains effective even “when [dust] soiling accumulates for 5 years” exclusive of bird droppings. The findings are localized to the Phoenix metropolitan area, and given the date of the study and possible urban construction and other environmental changes over the past fourteen years the findings may no longer represent real-world results for the Phoenix metropolitan area [10].
One study performed in Southern California [11] shows that cleaning is economical at an energy value of about $0.25 / kWh. The cleaning cost is an issue for commercial systems, as the cleaning crew has to receive payment for their work. In the case of residential systems, this problem is not so pressing, as it is the owner of the house who cleans the modules.

In 2006, Kimber et al. developed an empirical model to predict and quantify energy lost due to soiling [7]. The data points were determined based on soiling levels and a linear relationship was assumed between the data points. The study showed a performance loss due to soiling to be about 0.0011kWh/kWp/per day and a two to six percent annual energy loss based on over 50 large, grid-connected PV systems (including flat, tilted and tracking mounting systems) in arid regions of the U.S.

To further investigate existing predictive models, during 2006 to 2007 a study was performed by the SunPower Corporation [11]. It uses data obtained from three identical PV systems mounted on SunPower’s PowerGuard insulated roofing system. Observations were made at 15 minutes intervals. The systems were oriented in a way so that sun exposure and wind patterns were practically identical for all the three of systems. The main assumption of the study is that varying cleaning frequency would produce correlated energy output levels [11]. All the effort was directed at maintaining identical conditions for the systems and the tests were conducted during day periods in southern Carolina with no rain. The only feature that was different was the frequency of respective cleanings. The controlled experiment began in May 2006 and ended in December 2006. The
The first unit (A2) was cleaned twice in that period, once in July and again in September. The second unit (B1) was cleaned once and the third unit (B2) was left unwashed.

The A2 unit was considered a benchmark for negligible or small efficiency losses. The effect of cleaning was obvious, as power input increased each time the unit was cleaned. This variable was comparatively constant for A2, which was conditioned by well-organized cleanings. Rainfall that took place on October 13, 2006 had a positive effect for all the units.

Cleaning of the 100 kWp Solar PV Systems was $800 per cleaning. The first unit, A2, that was washed twice produced 8,000 kWh more energy than the system B3 that was never cleaned. The second unit, B2, that was washed one time, produced about 2,700 kWh more than B3. The value of the produced energy benefits is not greater than the cost of cleaning, and then the study’s conclusion is that cleaning is not cost-effective. However, any system installed under the California Solar Initiative will raise system annual revenue by $1,500 USD per 100 kWp capacity in Los Angeles, California due to cleaning. European tariffs are even more appealing, as a bi-annual cleaning would increase annual revenue by $3,000 per 100 kWp capacity.

The Mitchell et al. model [7] predicts annual soiling losses in energy output by 2% to 6% depending on the region and environment with respect to each different region. The study in Southern California [11] measured an output loss of 5.1%, which validates the above-described model. The model developed that predicts energy loss due to soiling is within a 3.5% degree of error.
2.2 Summary and Findings

It is very important to understand the adverse effects of soiling and how to reduce and control these effects, as it is one of the largest factors in system performance. Based on the Mitchell et al. study [7] and the SunPower South California study [11] soiling losses can be defined as approximately 5% of total reduced energy output. Based on the latter study, cleaning is economical at an energy value of about $0.25 per kWh. As demonstrated by Mitchell et al., efficiency losses caused by soiling vary greatly by geographic and climate region. Optimal cleaning recommendations should vary by region and climate to achieve the maximum economic benefit.

The PV’s efficiency is the measurement of system performance, which is affected by certain major parameters. These parameters include, but are not limited to:

- **Different technology**: There are many technologies available in the market, which range from 10% to 20% efficiency.

- **Temperature**: Power is influenced by temperature. As temperature goes up, power goes down.

- **Orientation**: PV should always be facing true South in the northern hemisphere between latitudes of 23 and 90 and opposite for the southern hemisphere.

- **Tilt angle**: Tilt angle affects performance because of the seasonal change of the sun’s location.
• **Shading:** PV technology is very sensitive to shading; when one spot is shaded, it affects the whole module.

• **Irradiance potential:** Depending on location, there is more or less irradiance on a day that is available for PV.

PV is influenced by different factors and all of them should be taken into account in the studies to obtain valid results. Soiling, however, has considerable influence over PV modules and this is why it is important to carry out further studies.

2.3 Incident Angle

In any outdoor experiment natural sunlight is used because that gives the best real environment for studying PV behavior. In this experiment natural sunlight is used because it provides the best real environment for studying PV behavior. The following model can be used for the incident angle effect [12]:

![Figure 2.1 How to calculate the radiation incident on a tilted surface](image)

The following equation expresses the solar radiation incident on a tilted module surface, which comprises the incident solar radiation that is perpendicular
to the module surface. With these variables the radiation incident on a tilted angle can be calculated.

\[ S_{\text{horizontal}} = S_{\text{incident}} \sin(\alpha) \quad (1) \]

\[ S_{\text{module}} = S_{\text{incident}} \sin(\alpha + \beta) \quad (2) \]

where:

\[ \alpha \quad = \text{Elevation angle (°)} \]

\[ \beta \quad = \text{Tilt angle of the module measured from the horizontal (°)} \]

2.4 Solar Energy

The energy output of common generators is acquired by integrating with time; however the power performance of a PV module depends on many factors, such as module temperature, irradiance, spectral response of the module, and characteristics of the module itself. Generally, the energy is calculated from the daily power production by numerical integration according to the equation below [4]:

\[ E = \Delta t \times \sum_{i=1}^{n} P_i \quad (3) \]

where:

\[ E \quad = \text{Module output energy (Wh)} \]

\[ \Delta t \quad = \text{Data sampling interval (hours)} \]

\[ P_i \quad = \text{Power at the } i^{\text{th}} \text{ sample time (W)} \]

2.5 Effect of Temperature Coefficients

Operating temperature greatly affects the power model. As the temperature of a PV cell increases, the power output decreases due to the change
in the silicon materials. The effect of temperature on a PV cell in relation to the standard test condition (STC) is determined by the use of temperature coefficients. The standard test condition is used as a way of normalizing power ratings of PV modules and is equal to an irradiance level of 1,000 W/m² at a cell temperature of 25°C. When modules are tested under standard conditions, this allows for the comparison of the power rating of one module to another without having to factor in the effect of irradiance and temperature. The disadvantage of this method is that testing conditions are often not typical of real world operating conditions and may not give an accurate representation of how a module will perform in the field. It can be useful to know what effect the site-specific temperature will have on the performance of a module. Its effect is often calculated using temperature coefficients. The temperature coefficients for maximum power ($P_{max}$), open circuit voltage ($V_{oc}$), and short circuit current ($I_{sc}$) are usually listed in the manufactures specification sheet for each module. The coefficients represent a % change in $P_{max}$, $V_{oc}$, or $I_{sc}$ for every °C the cell temperature differentiates from standard test conditions. The coefficient for $P_{max}$ can be used in Equation (4) to determine the percent power change of a PV cell due to operating temperature [13].

\[
\text{% Change } P_{max} = \left( T_c - T_{stc} \right) \times \left( \frac{\text{Temp Coeff } P_{max} \%}{°C} \right) \tag{4}
\]

where:

$T_c$ = Cell Operating Temperature (°C)

$T_{stc}$ = Standard Test Conditions Temperature (25°C)
Similar equations can be used to determine the % change in $V_{oc}$ and $I_{sc}$ of a module at operating temperature. A plot of the effect of temperature on $I_{sc}$, $V_{oc}$, and $P_{max}$ is shown in Figure 2.2 using example coefficients. Each module has its own specific coefficients based on the properties of the materials in which it is made, but are generally similar to the coefficients given in this example.

![Figure 2.2 Effect of Temperature on PV Cell Using Example Coefficients](image)

Figure 2.2 Effect of Temperature on PV Cell Using Example Coefficients [13]

As the cell temperature rises in Figure 2.2, the $V_{oc}$ and fill factor decrease while the $I_{sc}$ slightly increases. The overall result is a decrease in $P_{max}$ with an increase in temperature. Since STC conditions also include an irradiance of 1000 W/m², this plot shows that the ideal operating conditions for a PV cell is at high irradiance with low temperature [13].
2.6 Irradiance Calculation

The irradiance $G_o$ shall be calculated from the measured short circuit current ($I_{sc}$) of the PV reference device, and its calibration value at Standard Test Conditions, STC ($I_{rc}$). A correction should be applied to account for the temperature of the reference device $T_m$ using the current-temperature coefficient of the reference device $\alpha_{rc}$.

$$G_o = \left( \frac{1000 \times I_{sc}}{I_{rc}} \right) \times \left( 1 - \alpha_{rc} (T_m - 25) \right)$$

(5)

Where:

- $G_o$ = Calculated irradiance (W/m²)
- $I_{sc}$ = Measured short circuit current (mA)
- $I_{rc}$ = Calibration value at STC (mA)
- $\alpha_{rc}$ = Current-temperature coefficient (%/°C)
- $T_m$ = Temperature of module (°C)
CHAPTER 3

METHODOLOGY

3.1 Effect of Tilt Angle on Soiling

Estimation of the effect of tilt angle on soiling is based on field data acquired under natural sunlight with outdoor installed equipment. The methodology is designed to discern the difference between the irradiance measured by each specific tilt angle by calibrated clean and unclean solar PV modules. To ensure the accuracy of the irradiance, the modules were cleaned manually every other day to remove any dirt or bird droppings on the surface of the module. The bird droppings were also removed from the unclean modules using sharp pins. The bird droppings were removed because only the soiling effect was being analyzed. If the bird droppings were left on the soiled modules it would not be an accurate representation of the effect of tilt angle on soiling. In order to accurately remove the bird droppings a needle point was used to not disturb any of the soiling accumulated already. Bird droppings were a major problem since they were affecting the results in the beginning. In order to try to scare the birds away, metal spikes were installed on the metal frame where the solar modules were installed. These metal spikes helped immensely cut back on the bird droppings on the solar modules compared to what they were getting the beginning.

The data was downloaded from the data logger every week. The collected data was verified by comparing them to National Renewable Energy Laboratory’s (NREL) irradiance data from a nearby location in Phoenix. This was done to
analyze the systems accuracy. As a result, the comparison analysis of the sites is shown in the results chapter.

The effects of soiling on both clean and unclean measurements were compared. The data was only collected and monitored from the beginning of January 2011 and will continue to be collected beyond the completion of this thesis.

In this report, the data obtained between January 2011 and March 2011 is analyzed and presented. Details of the methodology of monitoring the data for each module in the field are presented in this chapter.

3.2 System Installation

The test systems were set up at the Photovoltaic Reliability Laboratory on the ASU Polytechnic Campus in Mesa, Arizona. The system included two parts: a clean and an unclean module array with different tilt angles. The system was installed at a minimum height of four and a half feet from the ground. This is mentioned because there are two perspectives that can be studied: one perspective is analyzing a PV system that is installed at 0° tilt angle at ground level. Then the second perspective is a PV system installed at 0° tilt angle at fifty feet above ground, i.e., on a commercial building. These two studies would hypothetically give different soiling losses due to the strong wind loads of the higher distance installed PV system. The theory is if a PV system is operating at this height, the wind load is much more frequent and stronger which then the solar module has less of a soiling effect. Still with this study and further investigation, it could possibly be interpolated at a given distance from the ground. However,
for this study the focus is on an open rack configuration at ground level for different tilt angles.

3.3 Photovoltaic Modules

As shown in Figure 3.1, each of the 18 mini frameless PV modules is made of eighteen polycrystalline silicon cells generating about 1 watt at standard test conditions (STC). This mini module typically generates about 170 mA at STC.

![Figure 3.1 Polycrystalline silicon solar cell sensor (rating: 1 W and about 170 mA short-circuit current under standard test conditions)](image)

There are eighteen calibrated mini solar PV modules (1 W each) placed on an open-rack configuration. These mini solar PV modules represent exactly a full size PV module. The dimensions of all the modules are five by five inches. These mini PV modules are made of eighteen polycrystalline silicon cells that are embedded in a solar glass material. This glass is for protection of the solar cells.
from the environment such as rain, dust and any external influence. The glass also provides high degree of transparency like any other full size PV module would.

Nine of the calibrated solar PV modules are on the left and nine on the right. The calibrated solar PV modules on the left in Figure 3.2 (b) represent the PV modules that are regularly cleaned every other day. The solar PV modules on the right that are never cleaned are the soiled solar modules. Below is Figure 3.2 that demonstrates the setup. Image (a) is the side view of modules at different angles. Image (b) is field experiment setup of eighteen mini solar PV modules with different tilt angles.
All of the modules are facing south and on an open rack configuration to simulate more of an open rack real field arrangement. The modules were tilted at an angle starting from zero degrees and increasing to forty degrees at five-degree increments, except for two that were tilted at a specific angle, i.e., one at $23^\circ$, $26^\circ$, $30^\circ$, $33^\circ$, and $40^\circ$. Figure 3.2 Tilt angles of modules
which is the common roof-tilt angle in Arizona, and another one at 33°, which is the latitude of the location, Mesa, Arizona. All the modules were installed away from surrounding structures to avoid shading.

3.4 Photovoltaic Module Calibration

Every photovoltaic module’s output terminals were loaded with a one-ohm precision resistor to monitor the short-circuit which is a measure of irradiance reaching the solar cells (typically, 170 mV generated across the resistor on clear sunny days because of typical short-circuit current of 170 mA at 1000 W/m²). A K-type thermocouple was attached on the back skin of each module to measure the module temperature.

Then, all modules were calibrated for \( I_{sc} \) (short-circuit current) linearity with irradiance and temperature. A PV module is a linear device when the applicable range of conditions is stated. Since the plot of \( I_{sc} \) versus irradiance and temperature is linear for the applicable range of conditions, the device is linear.

The procedure is based on IEC60904-10. It includes: 1) mesh screen light transmittance calibration, 2) module irradiance calibration, and 3) module temperature calibration.

The IEC 60904-10 standard describes the procedures utilized for determination of the degree of linearity of any photovoltaic device parameter in relation to a test parameter. A device is linear when it meets the requirements of section 7.3, which is stated as follows.
When some device is claimed to be linear, the applicable range of irradiance, voltage, temperatures, or other necessary conditions should also be stated. The requirements for the acceptable limits of non-linearity (variation) are:

- For the curve of short-circuit current versus irradiance, the maximum deviation from linearity should not exceed 2%.
- For the curve of open-circuit voltage versus the irradiance logarithm, the maximum deviation from linearity should not exceed 5%.
- If the temperature coefficient of short circuit current doesn’t exceed 0.1 %/°K, the device can be regarded as linear in relation to this parameter.

The light transmittance calibrations of the screens were achieved using the short circuit current values of the PV modules composed of large cells, based on IEC 60904-10. First four crystalline silicon commercial modules from different manufacturers were used for this screen calibration. It is assumed that each cell of the module generated the same amount of current. The average transmission of four modules instead of just one module was used to gain high confidence. The screens were designated as S-100 (smallest opening screen providing approximately 10% transmittance), S-200, S-400, and S-600 (largest opening screen providing approximately 60% transmittance). Then once the mesh screen light transmittance calibration values were calculated they were used to perform the module’s irradiance calibration for linearity. The table for the mesh screen light percentage transmittance for each different irradiance level that was used for the linearity calibration is located in Appendix A.
The irradiance and temperature calibrations were done at a chosen time on a clear day when the irradiance was about 1000 W/m\(^2\) or higher, and Air Mass (AM) was approximately 1.5.

For irradiance calibration, all the mini modules and two calibrated reference cells were mounted so that it was co-planar with 2-axis sun tracker. They were set up outdoors and operated under natural sunlight for about 20 minutes until the modules stabilize. The calibrated screens were placed onto the modules in turns with 2-inch distance to achieve different reduced irradiance levels. All the output values were recorded using a data logger to measure the irradiance.

For temperature calibration, the mini modules and reference cells on the 2-axis tracker started at a cool indoor place (ice was used to lower the temperature) to ensure a low module temperature, then they were moved outdoors. The temperature of all the modules gradually increased until a stable temperature was reached.

During the entire process, the temperature and voltage drop across the shunt resistors of all the modules and reference cells were recorded simultaneously every 30 seconds using a data logger. The recorded data were analyzed for linearity. The \(I_{sc}\) versus irradiance plots are given in Appendix B.

Figure 3.3 shows the modules during the temperature calibration process. The electrical specifications of these modules are given in Appendix C.
After the calibration, the modules were installed separately on the open rack. The voltage across the one-ohm resistor and the temperature of each module
were measured and recorded through the data acquisition system. Figure 3.4 shows the final system setup in the field.

![System Array in the field](image)

**Figure 3.4 System Array in the field**

3.5 Data Acquisition System

A CR1000 data acquisition system (DAS) was necessary to collect the extensive quantity of temperature and current data (across a one-ohm resistor as voltage data) over a three month period. The data was recorded every two minutes from each module daily and continues to be recorded. The system consists of one CR1000 data logger and two multiplexers, AM16/32 and AM416. The CR1000 is the main device for collecting and storing data. The multiplexers increased the input capacity beyond the channels integral to the CR1000. The thermocouple sensors are connected to the AM16/32 and the voltage outputs are connected to the AM416. Both multiplexers are connected to the CR1000. Figure 3.5 shows a photograph of the CR1000 with the AM16/32 below and the AM416 to the right of the data logger.
Figure 3.5 Data logger CR1000, Multiplexer AM16/32B and an AM416 relay multiplexer. The AM16/32B was used to record the voltage. The AM416 was used to record the cell temperature.

Short Cut is a software package that works with the Scientific Campbell data loggers. The software creates a program to tell the CR1000 what instruments are connected and how often to collect data from each instrument. Then the software, PC200W, uploads and downloads the program to the data logger. This program runs every two minutes, twenty-four hours a day and stores all the data in the data logger’s memory. The PC200W software connects and communicates the laptop to the CR1000 data logger through a RS-232 cable. Then about once a week, the data was downloaded to a laptop from the data logger. After the data was downloaded, it was imported into Microsoft Excel for further analysis. Figure 3.6 is a screenshot of PC200W.
Figure 3.6 Screenshot of PC200W software
CHAPTER 4
RESULTS AND DISCUSSION

4.1 Soiling at Different Tilt Angles

In this study, daily insolation losses of soiled modules from January to March 2011 were determined at different tilt angles. These losses were calculated using the baseline data obtained on the cleaned modules. The irradiance data was corrected based on the collected short circuit current and back sheet temperature of the test modules.

4.2 Soiling based on Experimental Results

Figure 4.1 shows the insolation losses corresponding to each tilt angle. The insolation values were calculated over a three-month period from January to March of 2011. The bars represent the complete average for the three months for each particular angle. First, the daily difference is calculated for each day starting from January 11th to March 31st. Then, the average is calculated for those values, represented by these bars. The graph signifies a decline in insolation loss as the tilt angle becomes more oriented towards latitude. As the tilt angle becomes increasingly horizontal, the insolation loss or soiling effect increases.
Energy losses vary from 1% to 4% with horizontal solar modules. For the latitude of 33° energy losses are not as great, but still vary from up to 3%, depending on the daylight conditions the amount of time it has been accumulating soil before rainfall. Rainfall makes a difference, because rain can act to clean the modules. This cleaning action generally only occurs when rainfall surpasses a certain value of approximately 4-5 mm per day [3]. During this study, there was rainfall which surpassed 5 mm, (based on Photovoltaic Reliability Laboratory’s (PRL) weather station), and it did effectively clean the solar modules from dirt accumulation. However, when there was only 1 millimeter of rainfall or less and no wind, it made the soiling effect much worse.

In Figure 4.2, a clear performance gain is noticed when the solar modules are cleaned by the rainfall. This figure also shows the rainfall values (in millimeters) accumulated each day.
Figure 4.2 Average daily insolation losses for 0° tilt angle and total rainfall in millimeters

It is evident how the poor conditions of February and rain affected the insolation. In the week of February 12th to the 20th, there were a few days where the weather was extremely overcast, cloudy, windy and rainy. This caused a significant difference in insolation drop from the previous week, but also helped wash the dust that had accumulated up until that date. During week seven, there was an obvious loss of the insolation due to bad weather, because there was a major storm that was affecting the irradiance levels. However, the rainfall of about seventeen millimeters, which was able to effectively wash the modules of dust, was significant enough to note. The week before, there was an average daily insolation of 4.78 kWh/m² for the unclean solar module and 4.97 kWh/m² for the clean solar module at 0° tilt angle. Until week six, there was a 3.87 % energy loss due to soiling. During the week where significant rainfall was encountered, the
insolation for both clean and unclean modules balanced to almost the same
insolation levels of about 3.74 kWh/m² for the clean module and 3.69 kWh/m² for
the unclean module, with only a 1.22 % soiling loss. As the rain and clouds
disappeared, the insolation levels went back up to normal levels for that time of
the season. However, solar PV modules rarely recover 100% of their capacity,
unless they are washed or a big rainfall occurs, as evidenced in week seven.

The rainfall was recorded using the lab’s weather station where the
experimental setup was installed. The rainfall is also included on the same plots
as the insolation losses. This helped provide a better understanding of how the
rainfall affected each tilt angle with soiling loss.

Figures 4.3 and 4.4 summarize the same insolation loss, due to the soiling
effect as Figure 4.2, but for 23° and 33° tilt angles. These tilt angles are
important, because they represent common tilt angles for Arizona. The 23° tilt is
the common roof pitch for many Arizona homes. The 33° tilt is the latitude
orientation of Mesa, Arizona, where the setup is located. The differences in these
figures are the insolation loss due to soiling, which are not as high as 0° tilt angle.
Table 4.1 summarizes these differences, and how the soiling effect is apparent in
rainfall, both before and afterward. Also, the figure shows how the setup only
recovered a percentage of its insolation capacity.
Table 4.1 Daily average insolation losses before rain and after rain for week seven

<table>
<thead>
<tr>
<th></th>
<th>0° Before Rain</th>
<th>23° Before Rain</th>
<th>33° Before Rain</th>
<th>0° After Rain</th>
<th>23° After Rain</th>
<th>33° After Rain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clean</strong></td>
<td>4.97</td>
<td>7.09</td>
<td>7.59</td>
<td>3.74</td>
<td>4.75</td>
<td>4.95</td>
</tr>
<tr>
<td><strong>Unclean</strong></td>
<td>4.78</td>
<td>6.94</td>
<td>7.45</td>
<td>3.69</td>
<td>4.71</td>
<td>4.90</td>
</tr>
<tr>
<td><strong>Insolation Loss</strong></td>
<td>3.87%</td>
<td>2.09%</td>
<td>1.85%</td>
<td>1.22%</td>
<td>0.82%</td>
<td>0.94%</td>
</tr>
</tbody>
</table>

The study shows a 3.87% insolation loss up to week six at 0° tilt angle, but only shows about a 2.09% insolation loss for 23° and an insolation loss of 1.85% for 33° tilt angles. It is assumed that the energy loss at this location due to soiling is the highest at tilt angles below 23°. This helps to illustrate the soiling effect after six weeks starting in January for this region, but more work is needed over longer study periods to help quantify these effects in greater detail.

![Daily Insolation Loss Due to Soiling](image)

Figure 4.3 Average daily insolation losses for 23° tilt angle and total rainfall in millimeters
Figure 4.4 Average daily insolation losses for 33° tilt angle and total rainfall in millimeters.

Figure 4.5 Average daily insolation values for clean and unclean solar modules for three months for all tilt angles.
Figure 4.5 is a summary of daily insolation values for January through March for all different tilt angles. The tilt angle is affected by the changing seasons; as the summer approaches, insolation values increase, but less so for the unclean modules. Values decrease with time, unless there is a rainfall or wind disturbing the dust accumulation.

Figure 4.5 also shows significant differences between energy losses from setting the tilt angle at 0°, 23° and 33°, respectively. They are not uniform, because there are often birds, clouds, rainfall and jets in the sky that can affect the daily insolation level, normal for a setup that is close to an Air Force base. The data is more uniformly distributed when calculated on a monthly basis. Monthly calculation is more appropriate for determining insolation levels for analyzing the data. When analyzing the data daily it is very sporadic, and uniformity affects variability, since soiling accumulation will be experienced differently every time within different years, due to a variety of factors, even at the same site. This is why more study is needed over longer periods - to help quantify these effects more completely.

Table 4.2 January to March 2011 insolation values and losses for clean and unclean solar modules

<table>
<thead>
<tr>
<th></th>
<th>Total Insolation (kWh/m²): January - March 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°</td>
</tr>
<tr>
<td><strong>Clean</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Soiled</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Insolation Loss (%)</strong></td>
<td>2.02%</td>
</tr>
</tbody>
</table>
The above table shows three months of insolation for the clean and unclean modules. The table demonstrates the impact that tilt angle has on soiling. The insolation difference between cleaning and not cleaning ranges from 2.02 % for the horizontal tilt to 0.96 % for latitude tilt. As mentioned previously, this indicates that anything between horizontal tilt and 23° tilt requires cleaning on a regular basis, but only if it is economically feasible. Table 4.2 is calculated by adding all the insolation values from January to March 2011, then calculating the difference as a percentage.

![Daily Insolation Loss Due to Soiling](image)

Figure 4.6 Daily insolation percentage losses for January through March 2011

Daily percentage losses in Figure 4.6 shows the sporadic values of insolation over a span of three months for 0°, 23° and 33° tilt angle. The graph shows how soiling is affecting solar module performance. In the beginning, there was no insolation loss and in early January, there is a rapid increase in insolation.
loss much faster than anticipated due to dust accumulation and no rainfall, which in week one there was about 0.51 millimeters of rainfall and no rainfall for two more weeks, which made the insolation on the soiled module get worse. Towards the end of January there was an almost 5% insolation loss because of the dry environment and no rainfall that occurred. Then, as the angle increases from zero degrees to thirty-three degrees, the insolation losses decrease, and are even more noticeable at 33°. The insolation loss for the 33° tilt angle has a small difference between clean and unclean data, thus showing little soiling effect at higher tilt angles.

As previously noted, these polycrystalline silicon solar cell sensors are calibrated for irradiance (W/m²). The irradiance on the cells is calculated through measurements of short-circuit current and temperature. The temperature effect on the short-circuit is corrected using the temperature coefficients previously calculated (electrical specifications are in Appendix C). These polycrystalline silicon solar cells have an uncertainty of approximately ±1% from sensor to sensor. This explains how, in February, there is a negative insolation loss due to soiling. That is because the measurement reached the sensor’s calibration limit.
Figure 4.7 Soiling comparisons on February 11, 2011 for clean and unclean modules at 0°, 5°, and 10° tilt angles

The above image and Figure 4.8 is a visual soiling comparison of the effect of tilt angle on soiling. The visual presentation along with the hard data collected, can further illustrate the effect of tilt angle on soiling. The zoomed in section in Figure 4.7 and a side-by-side comparison of Figure 4.8 can better describe the insolation losses. The first three solar PV modules are the clean ones.
and the second three solar PV modules are the unclean ones. The following results in Table 4.3 are the calculated insolation percentage losses at 0°, 5°, 10° and 23° tilt angles for February 11, 2011. Table 4.3 summarizes these losses on this particular day to show how the amount of rainfall makes a difference. The rain that fell on February 11th was approximately 1.27 millimeters of rainfall. The significance of this observation is that it suggests that, during a rainfall, less than 2 millimeters causes greater losses. When there is already dust accumulated on the solar PV module and a rainfall of less than 2 millimeters falls, the combination forms a dirt-like substance. The dirt created from the dust and small amount of rainfall actually starts to block the irradiance further. Then, Figure 4.9 shows how a major rainfall of 12.45 millimeters is able to effectively wash the solar PV modules from the soiling.

Table 4.3 Insolation percentage losses for February 11, 2011

<table>
<thead>
<tr>
<th>Insolation Loss (%)</th>
<th>0°</th>
<th>5°</th>
<th>10°</th>
<th>23°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insolation Losses:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>February 11, 2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insolation Loss (%)</td>
<td>4.33%</td>
<td>3.31%</td>
<td>2.82%</td>
<td>2.55%</td>
</tr>
</tbody>
</table>
Figure 4.8 (a) Cleaned and (b) soiled solar PV module for 23° tilt angle

(photographs were taken on the day before 2 mm of rainfall)
The soiling comparison in Figure 4.9, unlike Table 4.1, shows all the tilt angles, as well as how a major rainfall affects the insolation losses due to soiling on a particular day instead of a week. To further validate the rainfall cleaning, on February 19th, 2011 there was justification that rainfall could wash the solar PV modules after a major rainfall. On February 19th, there was approximately 12.45 millimeters of rainfall; this helped to validate the assertion that the insolation percentage losses calculated from the solar PV modules were almost zero, due to the heavy rainfall. Then, to compare the insolation losses before and after the rainfall, the averages were calculated. The averages were calculated from three days before and three days after the rainfall. The bars represent a percentage loss of insolation between clean and soiled solar PV module before and after February 19th. The figure shows exactly how a large rainfall of 12 millimeters or more can...
effectively wash solar PV modules in an environment that is comparable to Mesa, Arizona.

4.3 Validation of Experimental Data

To validate the experimental system for its accuracy, it was compared to the insolation values provided by the National Renewable Energy Laboratory (NREL). The accuracy of the system is within less than 1% difference from the actual values for this region, and the results are shown in Figure 4.10. These values are real insolation values from a nearby site in Phoenix.

![NREL vs. PRL Daily Insolation on Horizontal Plate](image)

Figure 4.10 NREL versus PRL Horizontal Plate
Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Soiling affect can be relatively large, compared to different balances of system performance loss factors. It is important that this effect be studied and accurately modeled in energy yield estimates. The study shows that, during the period of January through March 2011, for 0° tilt angle, there was a loss of approximately 2.02% due to soiling. This study for tilt angles 23° and 33° also have some insolation losses but do not have the same soiling effect as the 0° tilt angle. Tilt angle 23° had approximately 1.05% insolation loss, and 33° tilt angle had an insolation loss of approximately 0.96% in three months. The soiling effect is present at any tilt angle, but the magnitude is evident: the flatter the angle of the solar module is, the more energy it will lose. In addition to that, the effect of tilt angle on soiling is dependent on the environment.

The economics of system cleaning will differ by region, environment and energy savings. It is also important that the soiling effect is monitored with either equipment or regular visual inspection, and that action is taken when soiling losses become excessive to the point that it becomes cost effective to clean a PV system.

5.2 Recommendations

Further investigation is needed to determine the potential effects the seasonal change has on the soiling effect. This will help to determine performance loss and dust accumulation over a longer period of time.
REFERENCES


PV Systems.” *Home Power*, October/November 2009: 50-55
This appendix contains the calibrated irradiance mesh screen values for light transmittance.

<table>
<thead>
<tr>
<th>Caliration of Irradiance Screens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance (W/m²)</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>600</td>
</tr>
<tr>
<td>no screen</td>
</tr>
</tbody>
</table>
APPENDIX B

LINEARITY CHECK OF IRRADIANCE SENSORS
This appendix contains the linearity check of irradiance sensors for all eighteen modules in a table. The first two graphs are examples showing linearity of two solar PV modules.

Module 1A Irradiance Linearity Check

Module 2A Irradiance Linearity Check
<table>
<thead>
<tr>
<th>Irradiance (W/m²)</th>
<th>100</th>
<th>200</th>
<th>400</th>
<th>600</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clean</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module 1A</td>
<td>0%</td>
<td>-2%</td>
<td>0%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 2A</td>
<td>-4%</td>
<td>-2%</td>
<td>2%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 3A</td>
<td>-5%</td>
<td>-2%</td>
<td>1%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 4A</td>
<td>-3%</td>
<td>-3%</td>
<td>1%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 5A</td>
<td>-4%</td>
<td>-2%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 6A</td>
<td>-8%</td>
<td>-2%</td>
<td>1%</td>
<td>2%</td>
<td>-1%</td>
</tr>
<tr>
<td>Module 7A</td>
<td>4%</td>
<td>-2%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 8A</td>
<td>1%</td>
<td>-2%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 9A</td>
<td>0%</td>
<td>-2%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td><strong>Soiled</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module 1B</td>
<td>-3%</td>
<td>-1%</td>
<td>1%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 2B</td>
<td>0%</td>
<td>-1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 3B</td>
<td>1%</td>
<td>1%</td>
<td>-2%</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 4B</td>
<td>-4%</td>
<td>0%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 5B</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 6B</td>
<td>3%</td>
<td>2%</td>
<td>-2%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 7B</td>
<td>-2%</td>
<td>-2%</td>
<td>1%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 8B</td>
<td>2%</td>
<td>-1%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Module 9B</td>
<td>4%</td>
<td>2%</td>
<td>-1%</td>
<td>-1%</td>
<td>0%</td>
</tr>
</tbody>
</table>
APPENDIX C

CALIBRATED SHORT-CIRCUIT VALUES AND TEMPERATURE COEFFICIENTS FOR SOLAR PV MODULES
This appendix contains the calibrated short-circuit values and temperature coefficients for all eighteen mini solar PV modules.

<table>
<thead>
<tr>
<th>Module</th>
<th>mV @ 1000 W/m² and 25°C (1 ohm shunt resistor)</th>
<th>Temperature Coefficient (mV/°C)</th>
<th>Temperature Coefficient (%/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean Photovoltaic Sensors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1A</td>
<td>167.60</td>
<td>0.121</td>
<td>0.072%</td>
</tr>
<tr>
<td>2A</td>
<td>168.66</td>
<td>0.182</td>
<td>0.108%</td>
</tr>
<tr>
<td>3A</td>
<td>155.08</td>
<td>0.249</td>
<td>0.161%</td>
</tr>
<tr>
<td>4A</td>
<td>155.31</td>
<td>0.121</td>
<td>0.078%</td>
</tr>
<tr>
<td>5A</td>
<td>166.77</td>
<td>0.074</td>
<td>0.044%</td>
</tr>
<tr>
<td>6A</td>
<td>155.64</td>
<td>0.115</td>
<td>0.074%</td>
</tr>
<tr>
<td>7A</td>
<td>156.87</td>
<td>0.103</td>
<td>0.065%</td>
</tr>
<tr>
<td>8A</td>
<td>168.54</td>
<td>0.104</td>
<td>0.062%</td>
</tr>
<tr>
<td>9A</td>
<td>154.34</td>
<td>0.106</td>
<td>0.069%</td>
</tr>
<tr>
<td>Soiled Photovoltaic Sensors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1B</td>
<td>167.56</td>
<td>0.098</td>
<td>0.059%</td>
</tr>
<tr>
<td>2B</td>
<td>167.12</td>
<td>0.134</td>
<td>0.080%</td>
</tr>
<tr>
<td>3B</td>
<td>159.33</td>
<td>0.125</td>
<td>0.078%</td>
</tr>
<tr>
<td>4B</td>
<td>157.02</td>
<td>0.109</td>
<td>0.069%</td>
</tr>
<tr>
<td>5B</td>
<td>163.72</td>
<td>0.088</td>
<td>0.054%</td>
</tr>
<tr>
<td>6B</td>
<td>166.40</td>
<td>0.135</td>
<td>0.081%</td>
</tr>
<tr>
<td>7B</td>
<td>154.08</td>
<td>0.133</td>
<td>0.086%</td>
</tr>
<tr>
<td>8B</td>
<td>163.07</td>
<td>0.143</td>
<td>0.087%</td>
</tr>
<tr>
<td>9B</td>
<td>166.42</td>
<td>0.133</td>
<td>0.080%</td>
</tr>
</tbody>
</table>