

Photovoltaic Modules: Effect of Tilt Angle on Soiling

by

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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.

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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_{cell}) and short circuit current using a shunt resistor across each module to measure irradiance in the form of voltage (V_{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 coated 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

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]:

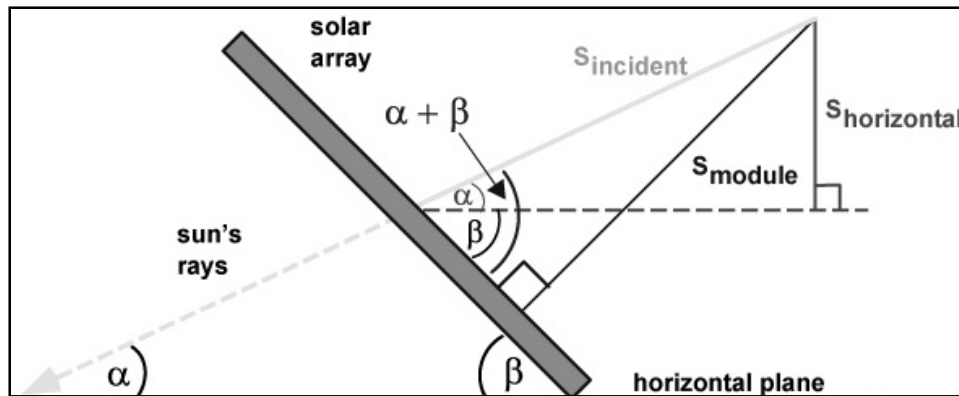


Figure 2.1 How to calculate the radiation incident on a tilted surface [12]

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:

α = Elevation angle ($^{\circ}$)

β = Tilt angle of the module measured from the horizontal ($^{\circ}$)

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 = Module output energy (Wh)

Δt = Data sampling interval (hours)

P_i = Power at the i^{th} 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].

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

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.

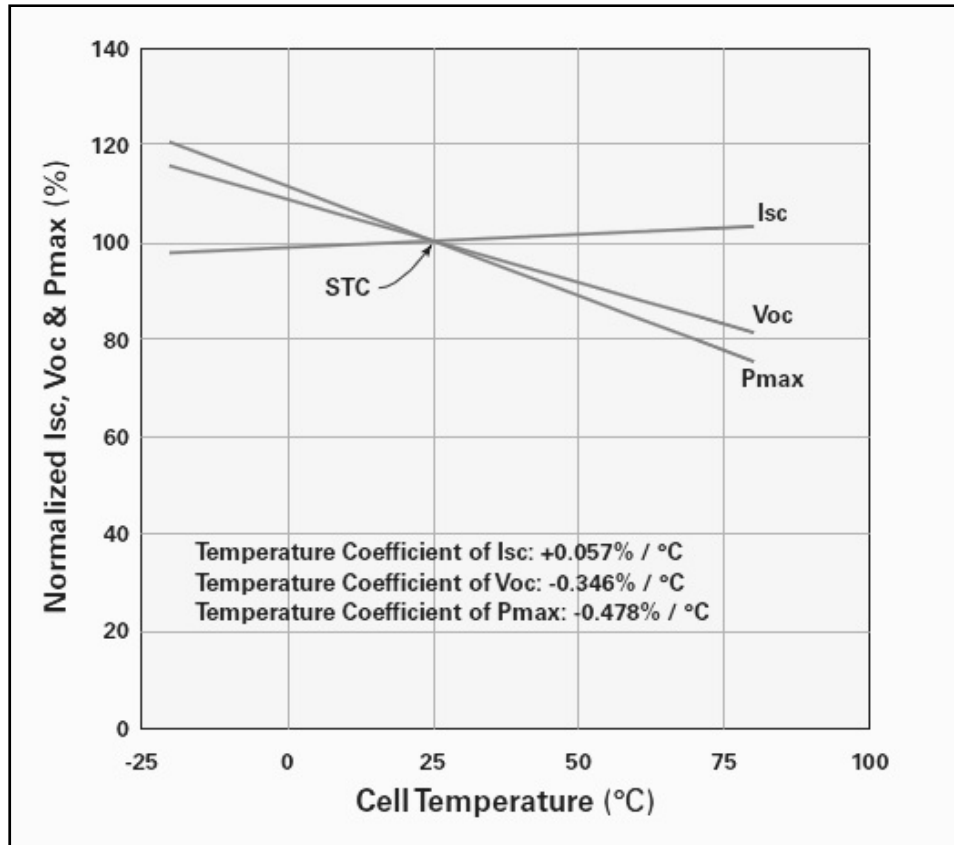


Figure 2.2 Effect of Temperature on PV Cell Using Example Coefficients [13]

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/m^2 , 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 α_{rc} .

$$G_o = \left(\frac{1000 * I_{sc}}{I_{rc}} \right) * (1 - \alpha_{rc} (T_m - 25)) \quad (5)$$

Where:

G_o	= Calculated irradiance (W/m^2)
I_{sc}	= Measured short circuit current (mA)
I_{rc}	= Calibration value at STC (mA)
α_{rc}	= Current-temperature coefficient ($\%/^{\circ}C$)
T_m	= Temperature of module ($^{\circ}C$)

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)

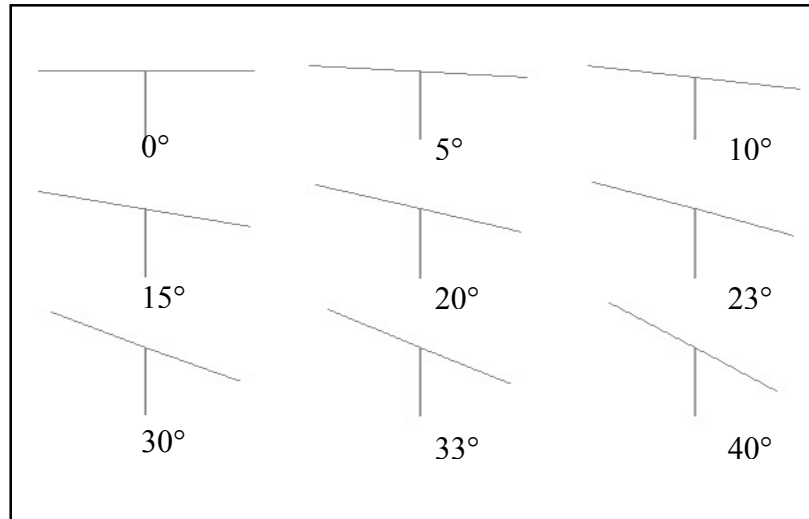
There are eighteen calibrated mini solar PV modules (1 W each) placed on an open-rack configuration. These mini solar PV modules represent exactly a full size PV module. The dimensions of all the modules are five by five inches.

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.

(a)



(b)



Figure 3.2 Tilt angles of modules

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°,

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.

(a)



(b)

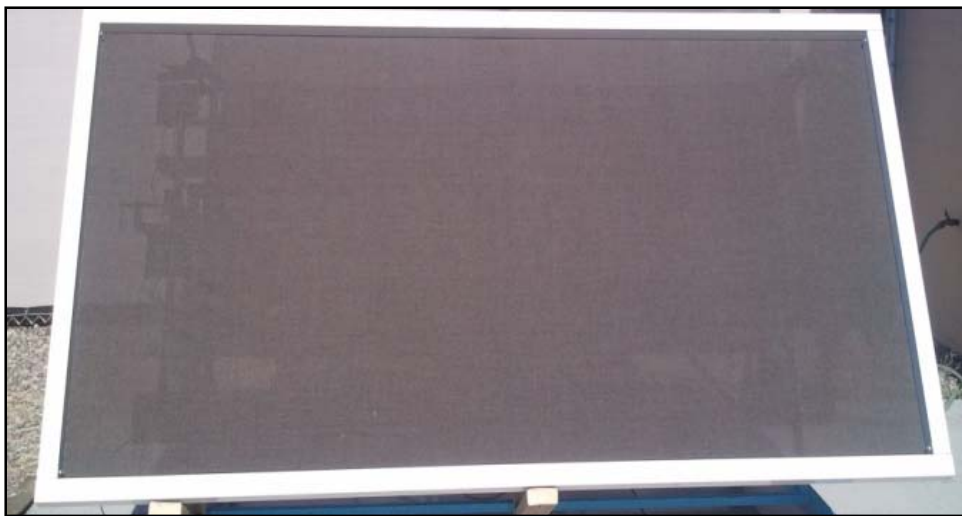


Figure 3.3 (a) Modules right before screen mesh (b) modules during linearity calibration

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.



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.

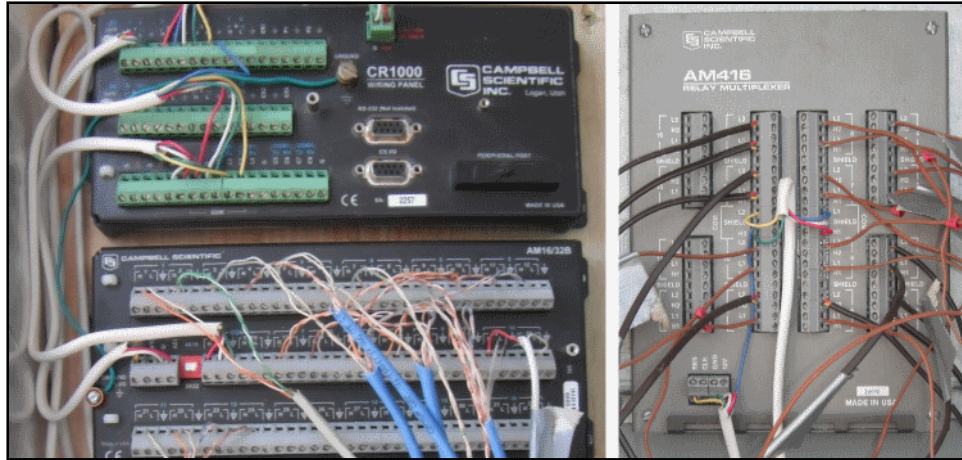


Figure 3.5 Data logger CR1000, Multiplexer AM16/32B and an AM416 relay multiplexer. The AM16/32B was used to record the voltage. The AM416 was used to record the cell temperature.

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.

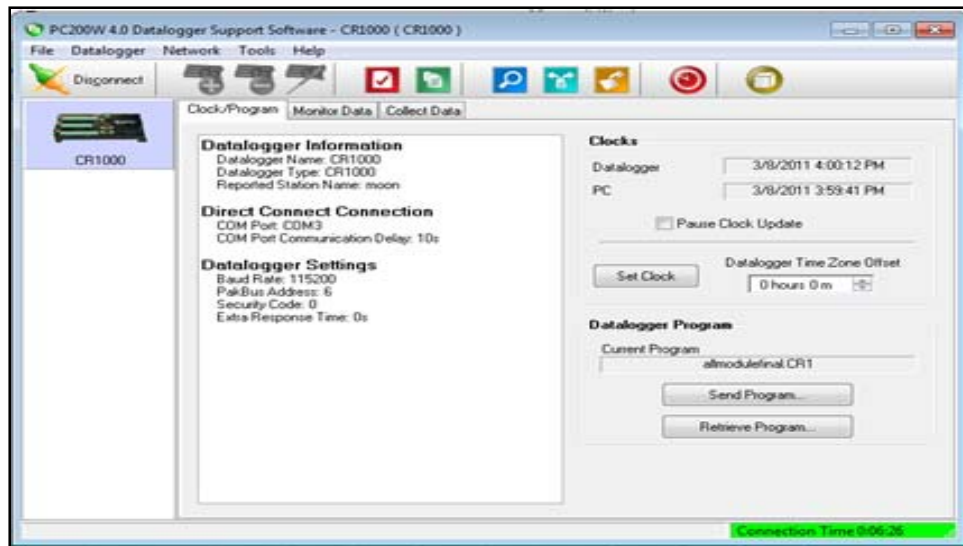


Figure 3.6 Screenshot of PC200W software

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.

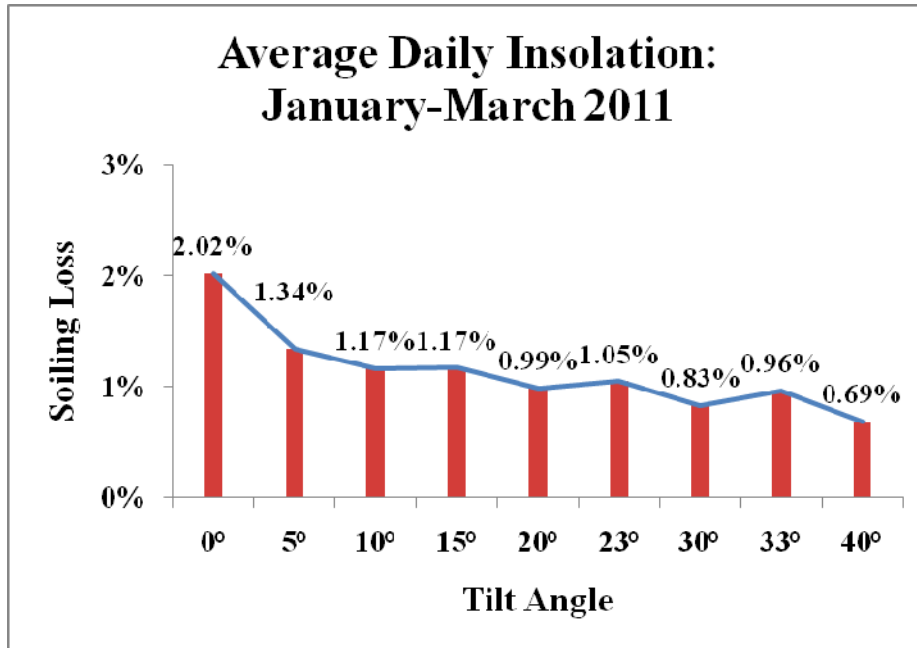


Figure 4.1 Insolation losses for each tilt angle from January through March

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.

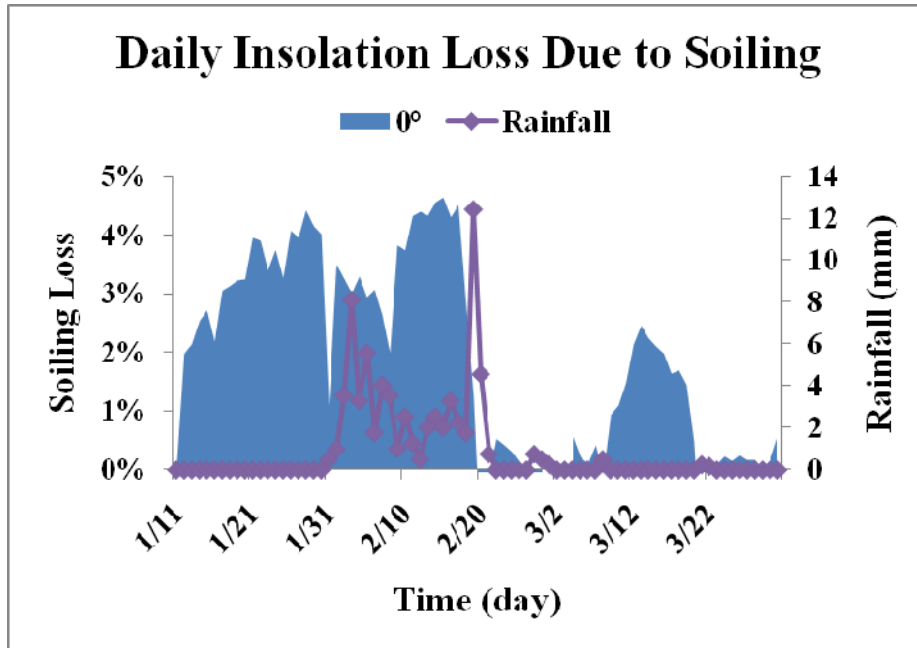


Figure 4.2 Average daily insolation losses for 0° tilt angle and total rainfall in millimeters

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

	Daily Average Insolation (kWh/m ²)					
	0°	23°	33°	0°	23°	33°
	Before Rain			After Rain		
Clean	4.97	7.09	7.59	3.74	4.75	4.95
Unclean	4.78	6.94	7.45	3.69	4.71	4.90
Insolation Loss	3.87%	2.09%	1.85%	1.22%	0.82%	0.94%

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.

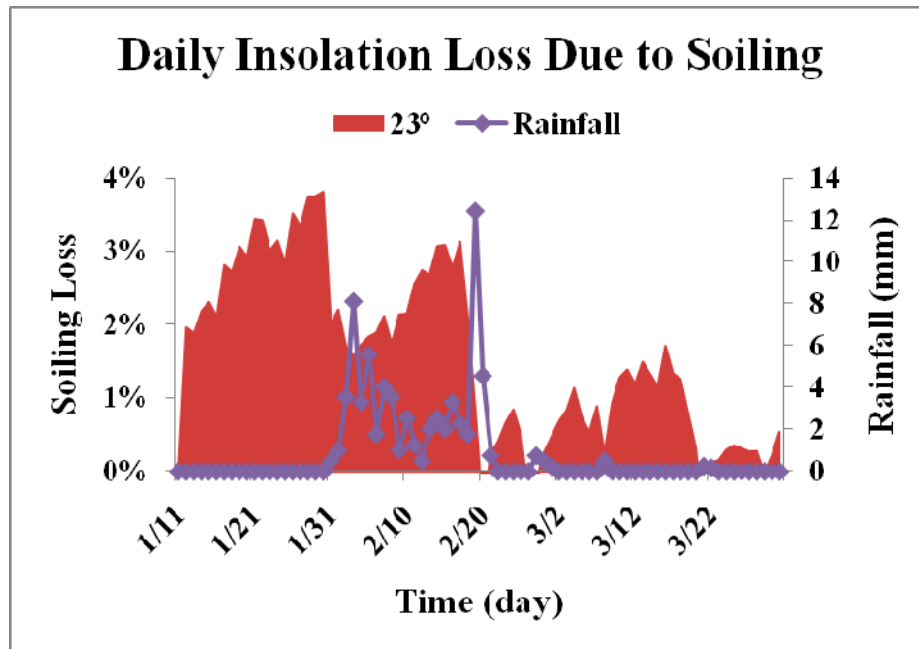


Figure 4.3 Average daily insolation losses for 23° tilt angle and total rainfall in millimeters

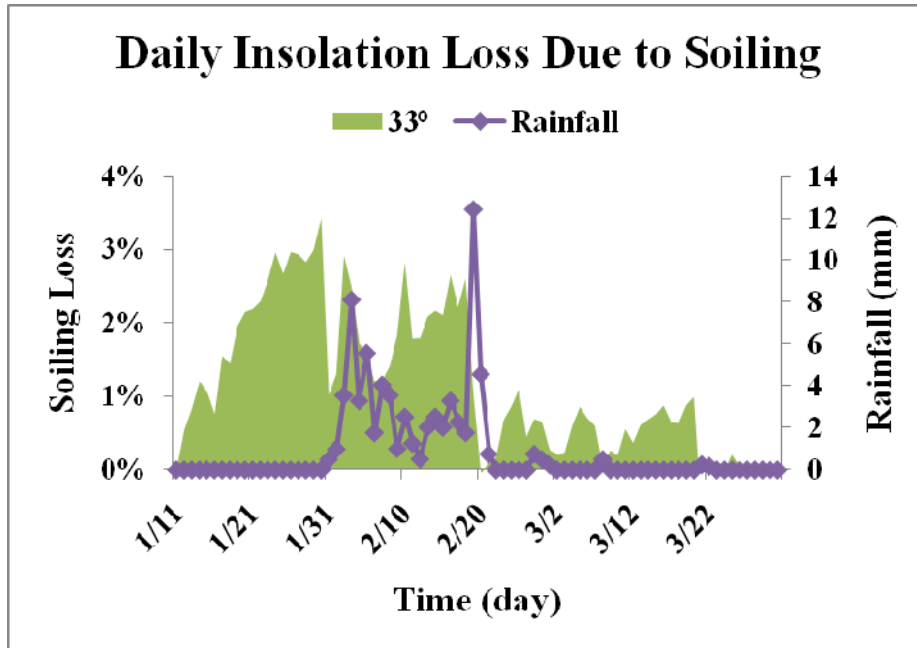


Figure 4.4 Average daily insolation losses for 33° tilt angle and total rainfall in millimeters

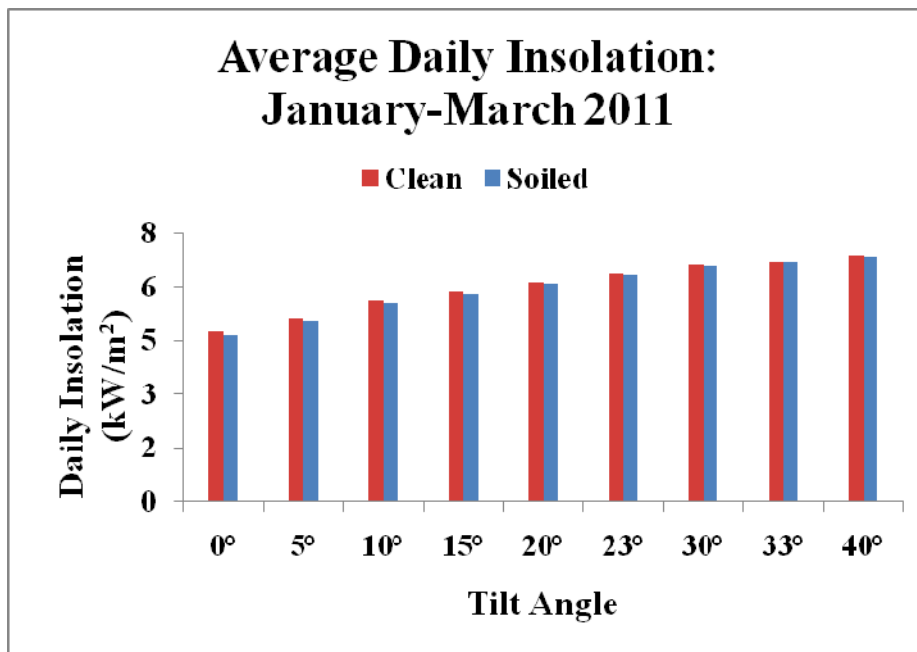


Figure 4.5 Average daily insolation values for clean and unclean solar modules for three months for all tilt angles

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

	Total Insolation (kWh/m²):		
	January - March 2011		
	0°	23°	33°
Clean	393.17	549.09	578.69
Soiled	385.24	543.33	573.11
Insolation Loss (%)	2.02%	1.05%	0.96%

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.

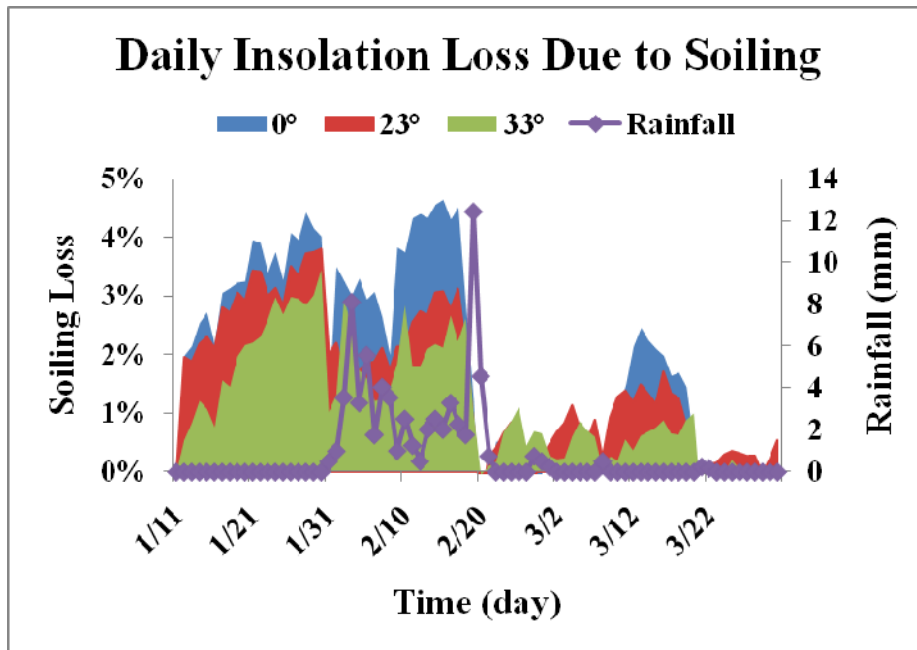


Figure 4.6 Daily insolation percentage losses for January through March 2011

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/m^2). 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 $\pm 1\%$ 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.

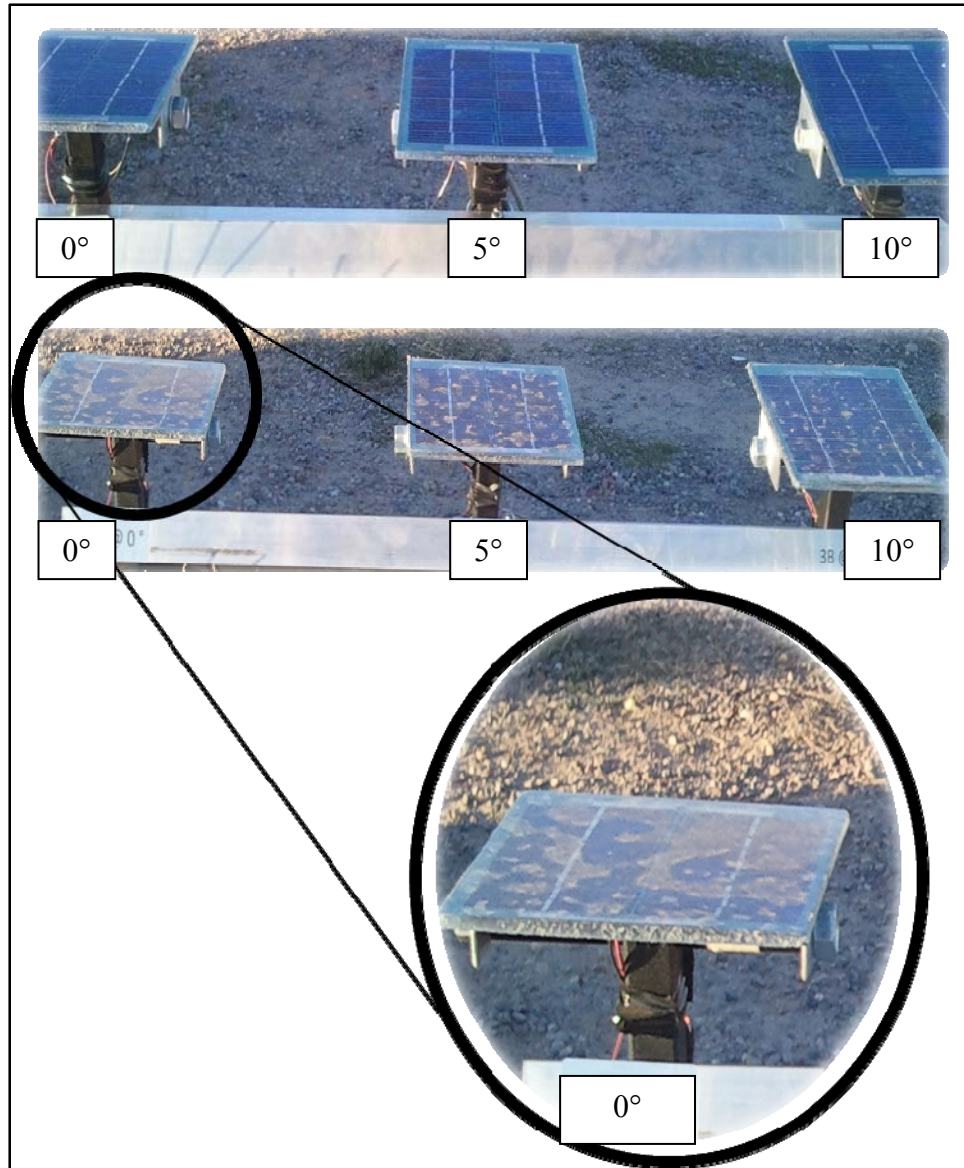


Figure 4.7 Soiling comparisons on February 11, 2011 for clean and unclean modules at 0°, 5°, and 10° tilt angles

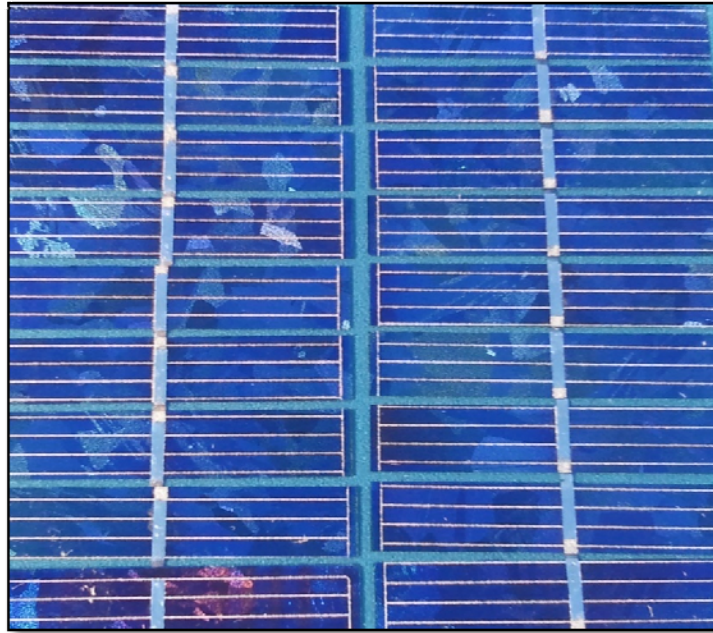
The above image and Figure 4.8 is a visual soiling comparison of the effect of tilt angle on soiling. The visual presentation along with the hard data collected, can further illustrate the effect of tilt angle on soiling. The zoomed in section in Figure 4.7 and a side-by-side comparison of Figure 4.8 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

Insolation Losses: February 11, 2011				
	0°	5°	10°	23°
Insolation Loss (%)	4.33%	3.31%	2.82%	2.55%

(a)



(b)

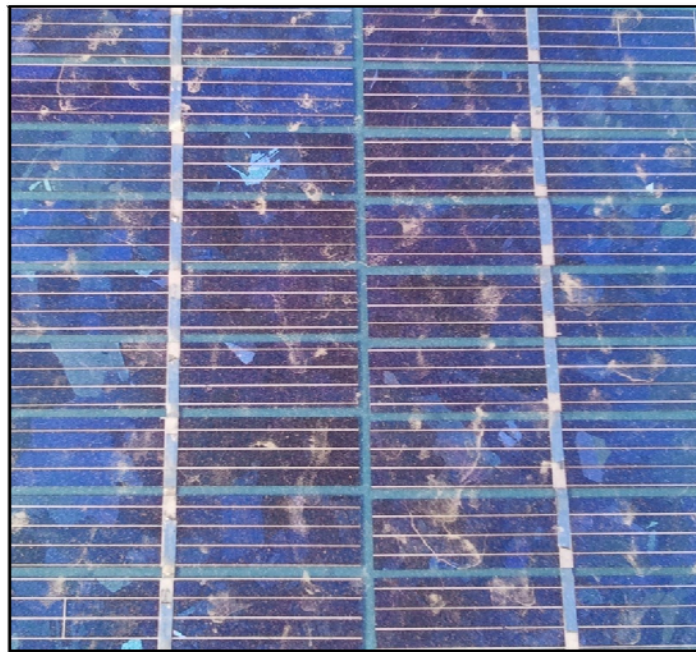


Figure 4.8 (a) Cleaned and (b) soiled solar PV module for 23° tilt angle
(photographs was taken on the day before 2 mm of rainfall)

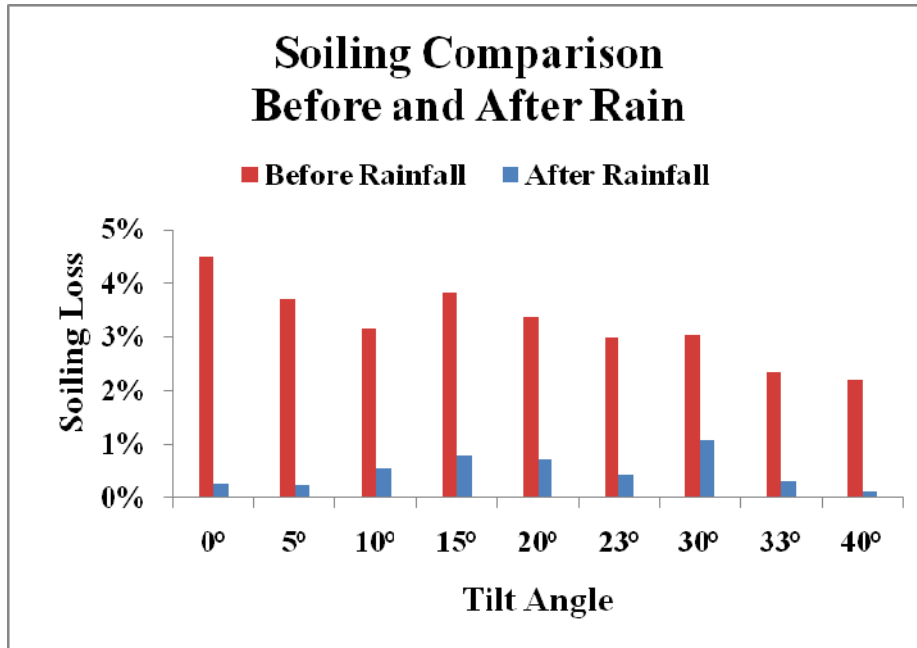


Figure 4.9 Soiling Comparison on February 19th, 2011 before and after rainfall

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.

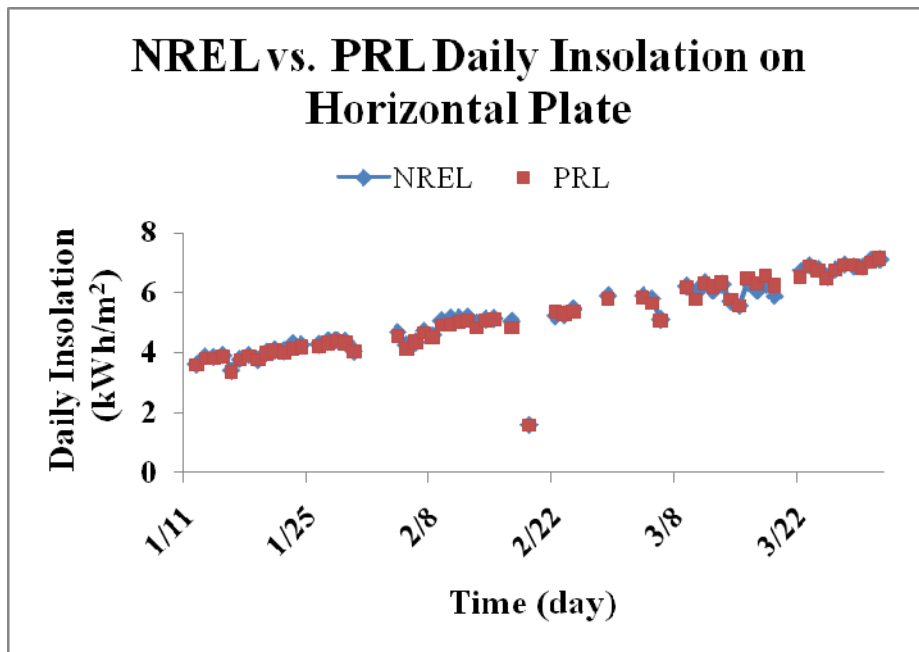


Figure 4.10 NREL versus PRL Horizontal Plate

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

- [1] Martin, N., Ruiz, J. M. A new model for PV modules angular losses under field conditions. *International Journal of Solar Energy*; 22(1), 19-31. 2002.
- [2] Martin, N., Ruiz, J.M. Calculation of the PV modules angular losses under field conditions by means of an analytical model. *Solar Energy Materials and Solar Cells*, 70(1), 25-38. 2001.
- [3] Hammond, R., Srinivasan, D., Harris, A., Whitfield, K., Wohlgemuth. Effects of soiling on PV module and radiometer performance. *Proceedings of the 26th PVSC*, 1121-1124.1997.
- [4] IEC 60904-10, International Electrotechnical Commission, *Photovoltaic devices: Methods of Linearity measurement*. 2011.
- [5] Roman, H., T. Converting Sunlight to Electricity-Some Practical Concerns. *Tech Directions*, 65(3), 24-25. Retrieved October 5, 2010, from ABI/INFORM Global. (Document ID: 916957521). 2005.
- [6] Garcia, M., Marroyo, L., Lorenzo, E., Perez, M. Soiling and other optical losses in solar-tracking PV plants in Navarra. *Progress in Photovoltaics: Research and Application*, 19(2), 211-217. March 2011.
- [7] Kimber, A., Mitchell, L., Nogradi, S., Wenger, H. The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest region of the United States. *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion*, 2, 2391-2395. 2006.
- [8] Levinson, R., Berdahl, P., Berhe, A.A., Akbari, H. Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane. *Atmospheric Environment*, 39(40), 7807-7824. 2005.
- [9] Massi Pavan, A., Mellit, A., De Pieri, D. The effect of soiling on energy production for large-scale photovoltaic plants. *Solar Energy*, 85(5), 1128-1136. 2011.
- [10] Qasem, H., Betts, T. R., and Gottschalg, R. Effect of shading caused by dust on cadmium telluride photovoltaic modules. Loughborough University, Leicestershire, LE11 3TU, UK. 2011.
- [11] Kimber, A. *The effect of soiling on photovoltaic systems located in arid climates*, Berkeley, CA, USA. 2007.

- [12] Martin, N., Ruiz, J.M. Annual angular reflection losses in PV modules. *Progress in Photovoltaics: Research and Applications*; 13, 75–84, 2005.
- [13] Mehalic, Brian. “Seeking Peak Performance: Lowering the Cost of Grid-Tied PV Systems.” *Home Power*, October/November 2009: 50-55

APPENDIX A

CALIBRATION OF IRRADIANCE MESH SCREENS

This appendix contains the calibrated irradiance mesh screen values for light transmittance.

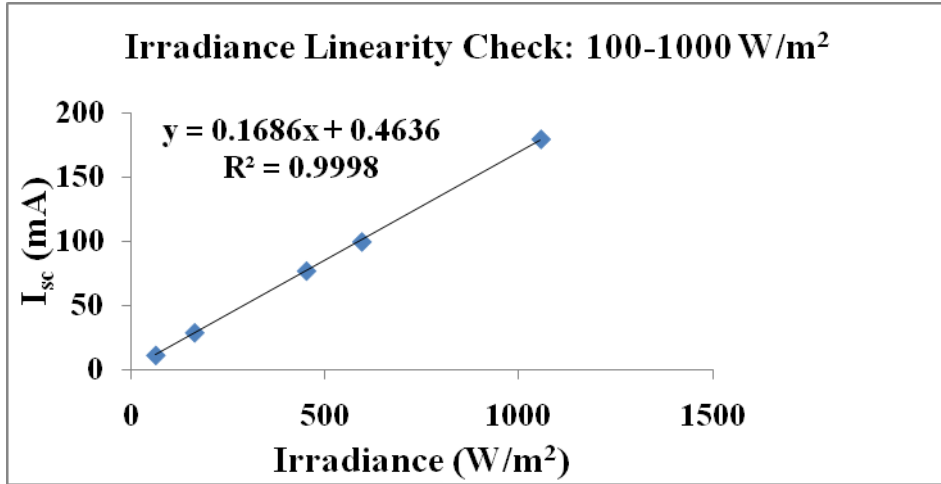
Calibration of Irradiance Screens	
Irradiance (W/m²)	Transmittance (%)
100	6.01
200	15.50
400	42.81
600	56.31
no screen	100.00

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

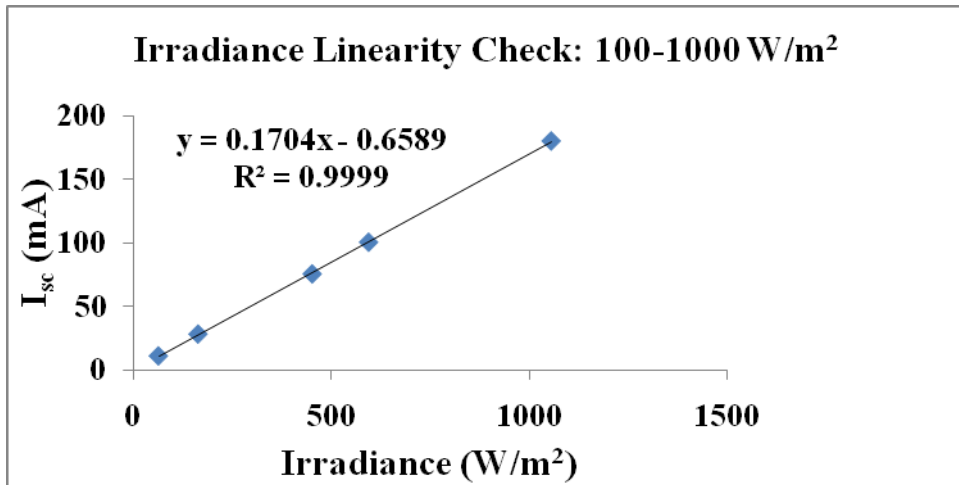


Table for Deviation from Linearity					
Irradiance (W/m²)	100	200	400	600	1000
Clean					
Module 1A	0%	-2%	0%	1%	0%
Module 2A	-4%	-2%	2%	1%	0%
Module 3A	-5%	-2%	1%	1%	0%
Module 4A	-3%	-3%	1%	1%	0%
Module 5A	-4%	-2%	1%	0%	0%
Module 6A	-8%	-2%	1%	2%	-1%
Module 7A	4%	-2%	0%	0%	0%
Module 8A	1%	-2%	1%	0%	0%
Module 9A	0%	-2%	0%	0%	0%
Soiled					
Module 1B	-3%	-1%	1%	1%	0%
Module 2B	0%	-1%	0%	0%	0%
Module 3B	1%	1%	-2%	1%	0%
Module 4B	-4%	0%	1%	0%	0%
Module 5B	1%	0%	0%	0%	0%
Module 6B	3%	2%	-2%	0%	0%
Module 7B	-2%	-2%	1%	0%	0%
Module 8B	2%	-1%	0%	0%	0%
Module 9B	4%	2%	-1%	-1%	0%

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.

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