Soiling of Photovoltaic Modules: Modelling and Validation of Location-Specific Cleaning Frequency Optimization

by

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ABSTRACT

To increase the deployment of photovoltaic (PV) systems, a higher level of performance for PV modules should be sought. Soiling, or dust accumulation on the PV modules, is one of the conditions that negatively affect the performance of the PV modules by reducing the light incident onto the surface of the PV module. This thesis presents two studies that focus on investigating the soiling effect on the performance of the PV modules installed in Metro Phoenix area.

The first study was conducted to investigate the optimum cleaning frequency for cleaning PV modules installed in Mesa, AZ. By monitoring the soiling loss of PV modules mounted on a mock rooftop at ASU-PRL, a detailed soiling modeling was obtained. Same setup was also used for other soiling-related investigations like studying the effect of soiling density on angle of incidence (AOI) dependence, the climatological relevance (CR) to soiling, and spatial variation of the soiling loss. During the first dry season (May to June), the daily soiling rate was found as -0.061% for 20^o tilted modules. Based on the obtained soiling rate, cleaning PV modules, when the soiling is just due to dust on 20^o tilted residential arrays, was found economically not justifiable.

The second study focuses on evaluating the soiling loss in different locations of Metro Phoenix area of Arizona. The main goal behind the second study was to validate the daily soiling rate obtained from the mock rooftop setup in the first part of this thesis. By collaborating with local solar panel cleaning companies, soiling data for six residential systems in 5 different cities in and around Phoenix was collected, processed, and analyzed. The range of daily soiling rate in the Phoenix area was found as -0.057% to

-0.085% for 13-28^{o} tilted arrays. The soiling rate found in the first part of the thesis (-0.061%) for 20^{o} tilted array, was validated since it falls within the range obtained from the second part of the thesis.

ACKNOWLEDGMENTS

Oh my Lord! All grace is due to you, which is befitting to your glorious presence and your great sovereignty. To my lovely parents, thanks for your unlimited love and care. To my wife, thanks for your support and patience. Many thanks to Dr. Govindasamy TamizhMani whose help and support paved me the way to learn and discover new things. It has been pleasure working under his supervision. My thanks to my committee members, Dr. Bradley Rogers and Dr. Deverajan Srinivasan, for their support and time. I am also very thankful to Joseph Kuitche, Sai Tatapudi, and all other PRL students who helped and worked with me.

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DEFENITION OF TERMS

PV = photovoltaic

ASU-PRL = Arizona State University Photovoltaic Reliability Laboratory

AOI = Angle of incidence

$\mathbf{I_{sc}}$ = Short circuit current (A)

CR analysis = Climatological Relevance analysis

CF = Cleaning Frequency

CFO = Cleaning Frequency Optimization

ET = Exposure Time (to natural soiling)

STC = Standard Test Conditions

WS= Wind Speed

RH = Relative Humidity

CRP (chart) = Cleaning cost versus Restored annual energy Price (chart)

FL (chart) = Financial Loss (chart)

CJ (chart) = Cleaning Justification (chart)

SCS = Soiling Checklist Sheet

STT = Soiling Testing Toolkit

SL = Soiling Loss

MSR = Monthly Soiling Rate

HBD = High Bird Droppings

LBD = Low Bird Droppings

PART 1:
MODELING SOILING LOSS USING MOCK ROOFTOP SETUP

1- INTRODUCTION AND STATEMENT OF THE PROBLEM

Introduction

The first part of this thesis is a detailed investigation on the progress of the soiling problem against the performance of those PV modules installed in cities like Mesa, AZ. Over time, more aerosols deposition results in increasing the soiling layer on the top surface of PV modules. On the other hand, other seasonal factors like dust storms, rainfalls, and high winds could help, hinder, or even stop the soiling progress.

Among different dust mitigation methods, water cleaning is the classic and more common solution. Washing the PV modules periodically is an effective method to maintain good performance of the PV modules. However, it is costly when conducted, especially in large-scale PV systems where washing the whole system needs hiring specialists and intensive use of water. For such systems, cleaning frequency needs to be optimized to ensure a balance between the annual cleaning cost and the loss due to soiling.

Need for the Project

This research project is of importance to those who are maintaining PV systems, including residential, commercial, and utility-scale kinds of systems. Since this project was conducted in the city of Mesa, AZ, the PV systems owners in this city, or in sister cities that have similar environmental conditions, directly benefit from the recommendations of this study. Additionally, this study provides other researchers, in different regions and countries, the procedure they can replicate to get the optimized cleaning frequency of the PV modules in their locations, taking the location-specific conditions into account.

Significance of the Project

Conventionally speaking, the lifetime of the PV systems is around 25 years. As cleaning the PV modules is a part of operation and maintenance (O&M) cost, one needs to consider the cost of the 25 years of cleaning when calculating the life cycle cost (LCC) of the PV system. Therefore, optimizing the cleaning frequency of the PV modules ensures avoiding unnecessary cleaning episodes, and performing necessary cleaning that restores energy that would be lost due to soiling. Thus, the output of this study has a direct influence on the economics of the PV systems, and in some cases on the feasibility of the solar energy investments.

Statement of the Problem

The objective of this study is to investigate the negative effect of soiling on the performance of the photovoltaic (PV) modules installed in Mesa, AZ, and also to find out the optimum cleaning frequency for those PV modules.

Research Objectives

This study has the following research goals:

- Coming up with daily rate of soiling loss and the optimum cleaning frequency for soiled PV modules in an economically justified way for PV systems installed in weather conditions similar to those in Mesa, AZ.
- Modeling the soiling progress over time, and studying the seasonal relevance to the soiling problem
- Studying the influence of the weather parameters such as wind, humidity, and dust storms on the soiling process
- Studying the variations in the soiling loss over the time of the day, i.e. with respect to the Angle of Incidence (AOI)
- Identifying the recommended days of the year to wash the PV modules in Mesa, AZ and similar cities.
- Spatial variation of the soiling loss

Limitations of the Project

This study has some limitations. One of those limitations is that not all the performance (I-V curve) parameters are measured in this study, assuming that the short circuit current (Isc) is the most affected parameter with direct and accurate proportion due to soiling. Another limitation is regarding the height of the mock rooftop used in this study, onto which the modules are installed. The height is not simulating the real rooftops exactly since the modules are closer to the ground level, which on the other hand gives an easier and safer access to the researchers at the Photovoltaic Reliability Laboratory (ASU-PRL). Most of the soiling measurements were done at relatively low angle of incidence (AOIs) which was good for increasing the accuracy of the calculations. However, in very rare cases, the AOI was relatively high which was, in turn, expected to affect the accuracy of measuring the soiling loss. The worst AOI of 52.21° was in day 88 of the experiment.

Definition of Terms

The following terms are commonly used in this project:

Short Circuit Current (Isc): The current output of a PV device in the short circuit (no load) condition.

Angle of Incidence (AOI): "The angle between the sun's rays and a line perpendicular to the array surface" (Dunlop, 2010).

Soiling loss: The performance loss in the PV modules due to soiling, or dust accumulation.

Soiling Rate: The average soiling loss per unit period of time, typically a day.

Summary

Soiling has a negative impact on the performance of the PV modules, therefore, on the economics of PV systems. The purpose of this project is to investigate the soiling effect in Mesa, AZ, and provide optimum cleaning frequency that helps reduce the annual cleaning cost and keep the PV systems in good performance. The next chapter covers a literature review on the main concepts for understanding the variations of soiling over time and their role in obtaining the optimized cleaning frequency of the PV modules.

2- REVIEW OF RELATED LITERATURE

Introduction

Soiling effect on the performance of the PV modules depends on the location of the PV installation, the climate throughout the year, and the exposure time of accumulating dust. The first part of this thesis focuses on the soiling effect versus time of exposure throughout the year. Different seasons with different weather parameters like rainfall, wind speed, and relative humidity, affect the soiling level build up on the top surface of the PV modules. In fact, the soiling loss even varies along the day with respect to the varying angle of incidence. Realizing the variations of the soiling losses throughout the year is important so that the cleaning frequency of the PV modules can be optimized.

Soiling Monitoring

Modeling the effect of the soiling on the PV modules over a period of time requires monitoring the performance of the PV modules over that period of time. By doing that, the pattern of the soiling effect over time will be obtained. Even though soiling depends on some random parameter like the weather conditions, soiling effect still has an almost fixed pattern from year to year.

Different previous studies have been conducted to monitor the soiling loss in different regions and settings. Kleissl et al. conducted one of the biggest studies on 186 PV systems in California. The research group compared the solar irradiance data from SolarAnywhere (SAW) database with the daily energy production of the PV systems to get the efficiency reduction; which was considered as the soiling loss. The study found the average daily soiling rate, in dry periods is 0.051% for the 186 sites (Mejia, and Kleissl, 2013).

Without comparison with any solar source models, Kimber et al. conducted a soiling monitoring study for PV systems in California and the southwest region of the United States. Using a 15-minute monitored data from the PV sites, the research group considered the soiling loss as the performance reduction of the PV modules over time, after correcting for the module temperatures. The study showed the average daily soiling loss in dry periods as 0.2%, resulting in an annual energy lost from 1.5% to 6.2%, for the different locations the study covered. Figure 2.1 shows the soiling monitoring that represents PV systems in Northern California (Kimber et al., 2006). Another important finding of this study was that it validated the linearity approximation of the soiling rate over the dry periods. In other words, soiling loss over dry periods is increasing almost linearly.

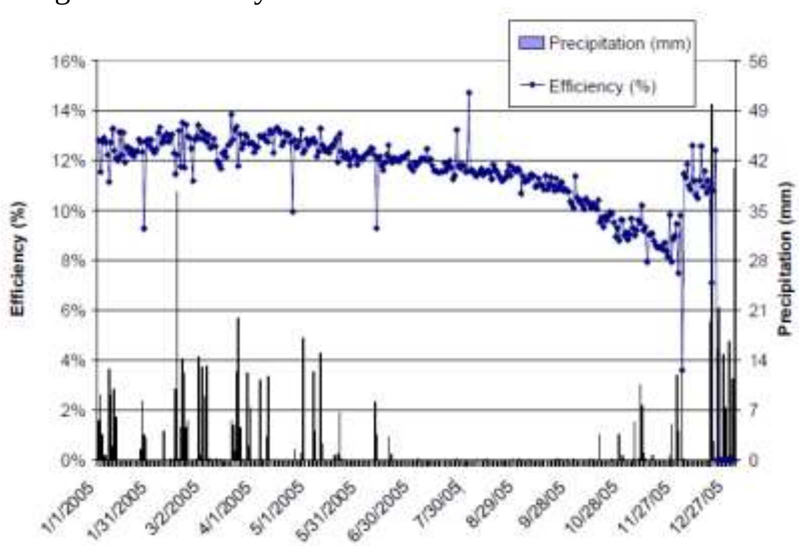


Figure 2.1 Soiling monitoring for Northern California (Kimber et al., 2006)

The above-mentioned studies were mainly based on monitoring the performance of the PV arrays/systems. Another experimental approach for soiling monitoring is based on the direct monitoring of the performance of PV modules rather than the PV arrays. The idea is based on monitoring the short circuit current, considering it the representative metric for the soiling loss. In the direct monitoring approach, each test module is short circuited through a current shunt which results in a voltage drop across it. By multiplying this voltage with a certain factor, the product represents the current flowing through the shunt which is the same as the generated current from the PV module. Taking the readings across the current shunt on a regular basis along the day and recording them by a data logger gives a detailed picture on how the module performs in terms of the short circuit current.

The idea was first proposed by Rayn et al. in their study at University of Oregon, and then adopted by other studies like the First Solar study by Caron and Littmann in California and the study conducted by Piliougine et al. in Spain. The First Solar study investigated the soiling loss along the year for two different environmental categories: desert and heavy agricultural regions. Figure 2.2 shows the soiling monitoring for PV systems installed in those two categories. The study found that in the heavy agricultural region, the monthly soiling rate was 11.5%, compared to 1% in the low desert region (Caron and Littmann, 20013).

The research group in the University of Malaga in Spain did two rounds of soiling monitoring. The first one was in 2006-2007, conducted by Piliougine et al. The study showed that soiling loss in dry periods could reach to 15%. The study also found that the annual loss factor on the PV performance due to soiling was 6%, which is larger than the default loss factor used in sizing the grid-connected PV systems which is 3%-4% (Piliougine et al., 2008). In 2008-2009, with some changes in the research group, Zorrilla-Casanova et al. presented more comprehensive soiling monitoring. The extra feature of that study was that it included more precise evaluation of the daily soiling loss since it considered the change of the soiling loss during the day. Figure 2.3 shows the soiling monitoring of that study from mid-December 2008 till mid-December 2009. In the Y-axis, HL refers to the absolute value of the soiling loss. The study showed that soiling loss could reach 20% in the dry periods without rain. From the data of the whole testing year, the mean of the daily soiling loss in one year was found as 4.3% (Casanova et al., 2012).

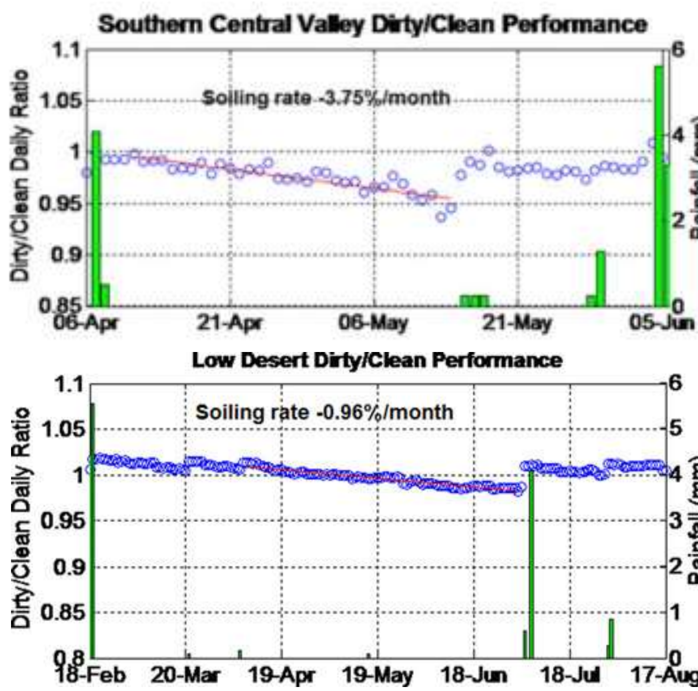


Figure 2.2 Soiling monitoring for PV systems in agricultural and desert regions (Caron and Littmann, 20013)

Soiling monitoring studies could be short term studies for a month or two, and they also could be long term for one year or more. An example of the short term is a study conducted in Italy by Pavan et al. where two 1 MW power plants were monitored after 8 weeks of soiling. The resulting decrease in performance was 1.1% of one power plant, and 6.9% for the other one (Pavan et al., 2011). An example of a long term soiling study is the one conducted by Ryan et al. where solar arrays installed in the University of Oregon were monitored over six years, from 1983 to 1988 (Ryan et al., 1989).

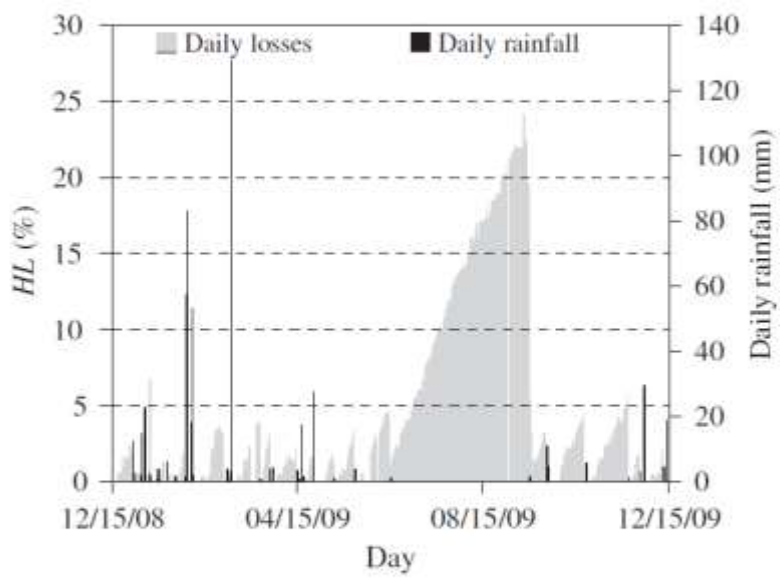


Figure 2.3 Soiling loss monitored by Casanova et al. (Casanova et al., 2012).

The long term soiling studies have the advantage of realizing the difference of the soiling effect from year to year, as was noticed in a study conducted by Townsend and Hutchinson, who monitored PV modules in Davis, California. Figure 2.4 shows the soiling monitoring in three metrologically different years: normal, dry, and wet (Townsend and Hutchinson, 2000). Another advantage of the long term soiling studies is that they show a clear picture of the common trend of the soiling, enabling the studies to come up with a reasonably accurate average for the soiling rate.

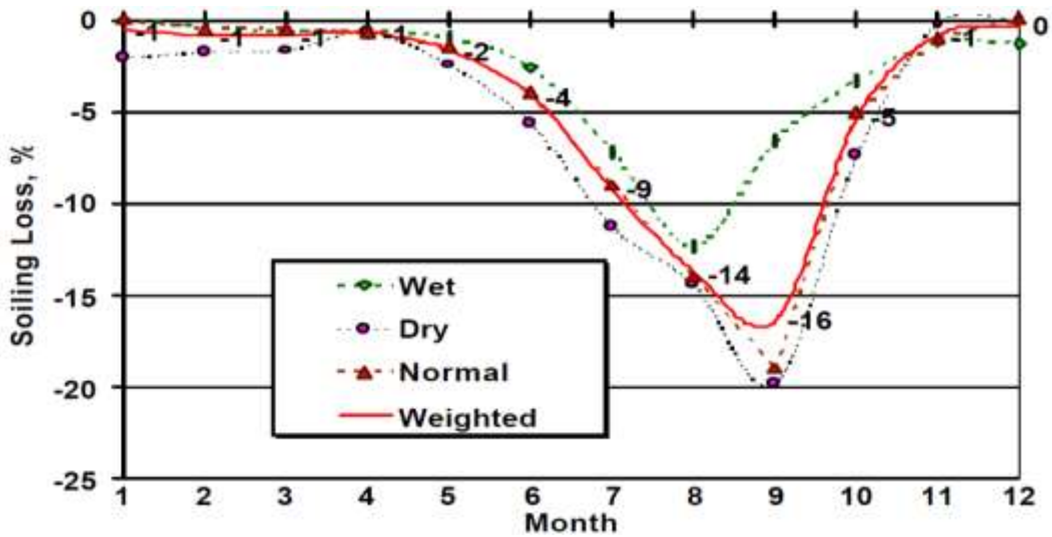


Figure 2.4 Soiling monitoring in Davis, CA(Townsend and Hutchinson, 2000).

Another good example of long-term soiling studies is what McCarthy Company revealed in an article written by Scott Canada. Soiling loss was monitored in two different locations in Arizona for 20 years. Figures 2.5 and 2.6 show the monitoring of the average monthly soiling loss for the two locations, and annual soiling loss for one of the two locations, respectively. After analyzing the soiling loss for different large PV systems in the Phoenix Metropolitan area, McCarthy Company announced the daily soiling rates in that area between 0.04% and 0.07% (Canada, 2013).

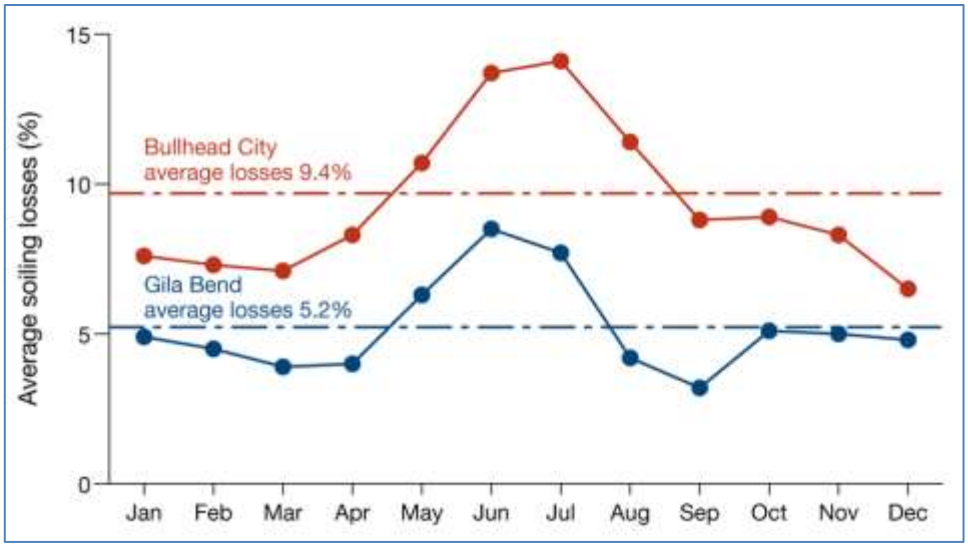


Figure 2.5 Average monthly soiling losses for two different locations in AZ (Canada, 2013)

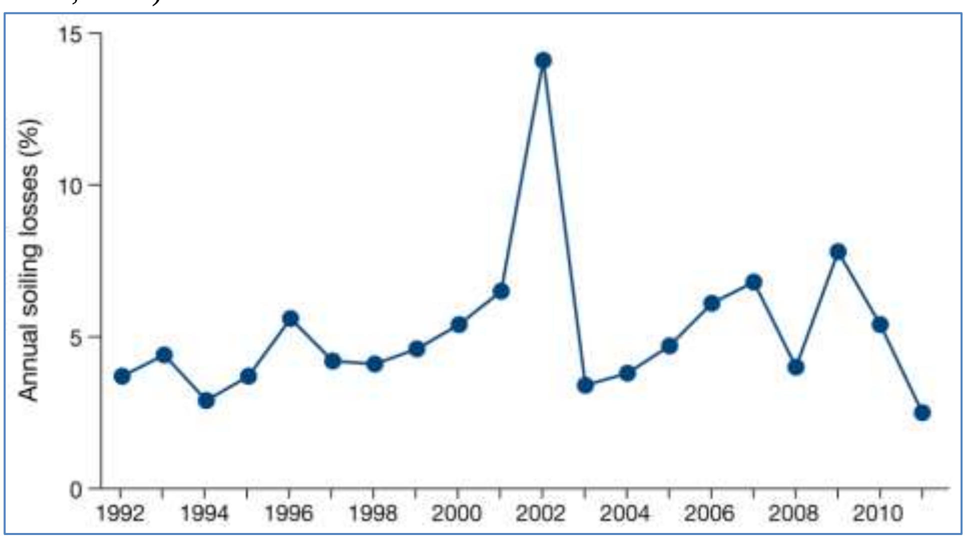


Figure 2.6 Annual soiling losses in Gila bend, AZ (Canada, 2013)

Soiling Loss Variations along the Day

In 1997, Hammond et al. published a paper on the soiling effect on PV modules and radiometers. In the same study, the Angle Of Incidence (AOI) effect on the performance loss due to soiling was pointed out. The soiling loss of the test

PV array increased from 2.3% at AOI of 0° to 4.7% at AOI of 24°, and to 8% at AOI of 58° (Hammond et al., 1997). The results of the just mentioned paper were a good start to draw more attentions toward the need for more detailed investigations on the AOI dependence of the soiling effect.

The above mentioned study was followed with a couple of more detailed ones. One of which was a study titled “Soiling and Other Optical Losses in Solar-Tracking PV Plants in Navarra”. The study was based on field measurements of a PV power plant located in Northern Spain. Both AOI and soiling losses were considered as optical losses. The study presented and compared those losses in three different cases: azimuth-tracking, 45-tilted, and flat-mounted PV modules. The study showed that horizontally mounted modules experienced more AOI and soiling losses compared to the azimuth tracking ones. Quantitatively speaking, it was found that the annual optical losses for the tracking modules were 3.8% (1% due to AOI and 2.8% due to the accumulated dirt) whereas the optical losses were 11.9% in the case of flat mounting of PV modules; 5% is AOI losses, and 6.9% is soiling losses (García et al., 2011).

Zorrilla-Casanova et al., in a paper titled “Losses Produced by Soiling in the Incoming Radiation to Photovoltaic Modules”, investigated the AOI dependence of the soiling loss for different levels of soiling density. As seen in figure 2.7, irradiance loss due to soiling (GL) increases as the AOI increases, with the minimum loss at the lowest AOI at noon time. The figure also shows that same curve is repeated with different soiling levels (Casanova, 2012). Another way to show the AOI dependence of the soiling loss was presented in a study titled “Validating an Angular of Incidence Losses Model with Different PV Technologies and Soiling Conditions” conducted by Martin et al. This is shown in figure 2.8, where the soiled module (blue curve) shows different AOI dependence than the clean module (red curve). The study also showed that the AOI dependence of the soiling loss was not affected by the type of the PV technology (Martine et al., 2012).

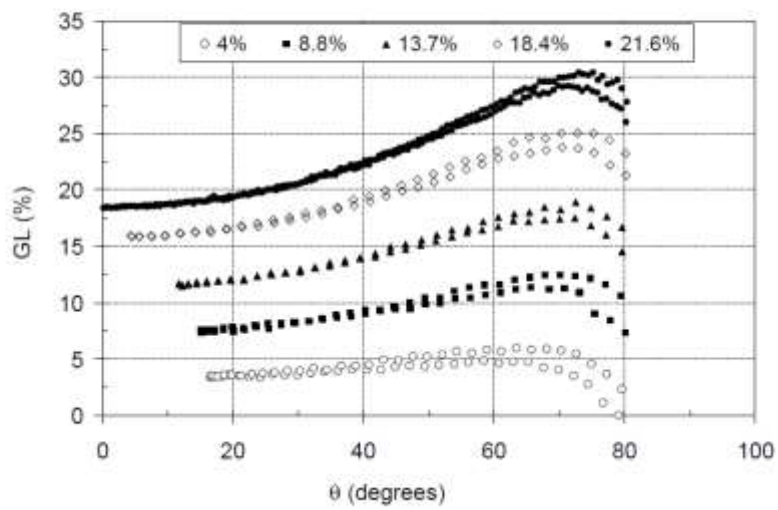


Figure 2.7 Irradiance loss due to soiling as a function of AOI (Casanova, 2012)

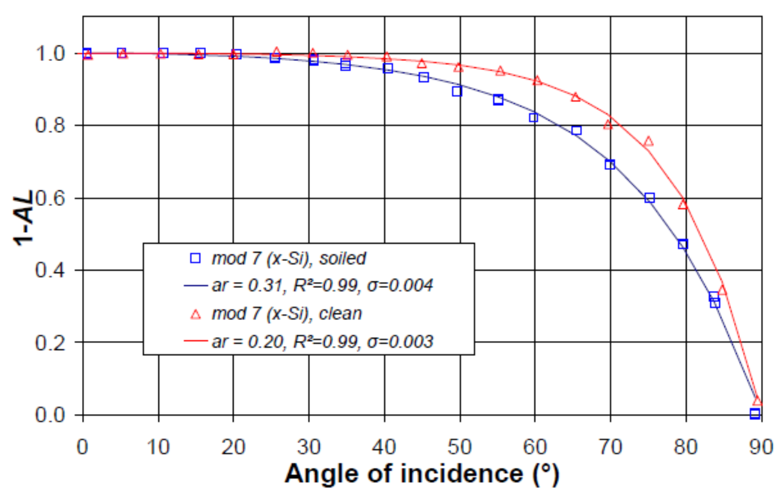


Figure 2.8 AOI dependence of the performance for both clean (red) and soiled (blue) modules (Martine et al., 2012)

Climatological Relevance to the Soiling Loss

Studying the climatological influence on the soiling is critical since it enhances understanding of the soiling process. Different weather parameters play roles in increasing or decreasing the soiling level. Starting with rainfalls, heavy rains are helpful since they clean the soiled solar modules, while light rains might increase the soiling since they may help the dust to be stuck more on the surfaces of the solar modules. Dry periods with the absence of rainfalls are usually the times where the soiling loss peaks during the year. Goossens et al. and others have done wind-related studies. They concluded that higher wind velocities result in higher dust depositions. However, high winds can also be good dust removers from the surface of the solar modules. Humidity is another factor that may worsen the soiling problem (Sarver, Al-Qaraghuli, and Kazmerski, 2013).

Dust storms are also weather-related events that affect the soiling process. They speed up the soiling process since they carry a lot of dust during their episodes. In Saudi Arabia, a study conducted by Adinoyi and Said showed that the performance reduction of PV modules can reach 20%. (Adinoyi, and Said, 2013).

Cleaning Frequency Optimization

Soiling is a cause of the performance reduction in PV systems. In fact, soiling losses should be considered for the whole lifetime of the PV systems. In some cases, the cost of the lost energy due to soiling can obviously influence the feasibility of the PV system investment. The value of the lost energy due to soiling could be higher in times when the peak soiling losses match with the increased electricity demand. In the high demand season in summer, the soiling loss reaches high values as the summer season lacks rainfalls. This situation is not good for the economics of solar power plants as they would not be able to meet the high demand in which some utilities pay more for the Kilowatt-hour. Therefore, manual cleaning of PV systems is an option to consider for the system operators in order to mitigate the soiling losses and the related financial consequences (Canada, 2013).

To make a decision of manually cleaning the PV system, several factors should be considered before that decision. One of those factors is the seasonability nature of soiling. Since soiling could be a seasonal problem more than an annual problem, studying the soiling loss in the location of the PV system is an important tool to determine in which season/period soiling would be the worst. Finding the soiling rates (soiling loss per day) is one of the most important products of the location-specific soiling studies. By knowing the soiling rate and the rainfall data, one can simulate and predict the annual energy loss due to soiling for any given year (Canada, 2013). Once the annual loss is estimated, the need of manual cleaning and its recommended frequency should be realized.

Evaluating the cost of the cleaning is another important factor to consider before deciding to go with the manual cleaning option. Solar panel cleaners usually charge per number of modules, which means large systems, like the utility-scale ones, cost a lot of money to get cleaned. Additionally, lost energy, due to switching off the PV system while cleaning, adds to the cleaning cost (Stridh, 2012).

One of the location specific factors that affect the soiling losses is the nature of the soiling itself. Soiling composition is different from one location to another. Soiling in PV systems near industrial areas could contain some of the byproducts emitted from factories (Sarver, Al-Qaraghuli, and Kazmerski, 2013). Soiling in coastal areas has salt content (SolarCleaner, 2011). In agricultural regions, more deposition of organic materials occurs on the top surfaces of PV modules (Sarver, Al-Qaraghuli, and Kazmerski, 2013). Realizing the nature of soiling is critical sometimes as some soiling content could be a serious performance killer for the PV modules. Bird droppings are a good example of that as they are much more opaque than other soiling content like dirt. Moreover, it is hard for the rainfalls to wash the bird droppings off the module surface (Gibson, 2013).

Summary

Soiling loss in a given PV site varies throughout the year from season to season. In fact, soiling even varies throughout the day from hour to hour. Monitoring, simulating, and modeling the location-specific soiling loss versus time helps in deciding if the cost of manual cleaning is justified. Using the soiling and climatological data for the location of the PV system is also helpful in determining the optimum cleaning frequency for the PV modules of that system.

3- METHODOLOGY

Introduction

The main framework of this project is centered on exposing PV modules to be naturally soiled, cleaning the modules with different cleaning frequencies, and setting up measuring and data logging systems to record the data needed for the analysis. This project was conducted in the Photovoltaic Reliability Laboratory (ASU-PRL) located in Polytechnic campus of Arizona State University in Mesa, AZ. Twenty four PV modules were mounted on a mock rooftop, facing the south with a tilt angle of 20° and a 3 inch air gap from the roof, which is close to the settings being followed by the PV installers in Arizona (see figure 3.1). Equipment needed to record the short circuit current (Isc) for all modules and to record the weather parameters were installed, wired, and set. In this chapter, the equipment used for data collection is presented, besides the methods used for data processing and analysis.

Figure 3.1 The mock rooftop used in the project

PV Modules Specifications

Poly-crystalline Si PV modules were used with top surfaces made of glass. All the modules had the same nameplate and rating. The electrical specifications for those PV modules are shown in Table 3.1. Each module is 1.5m long and 0.6m wide. The temperature coefficients of the voltage, current, and power are -0.45%/°C, 0.07%/°C, and -0.65 %/°C respectively.

Table 3.1

Electrical specifications of the test PV modules

Maximum Power (Pmax)	Maximum power voltage (Vm)	Maximum power current (Im)	Open circuit voltage (Voc)	Short circuit current (Isc)
95 Watts	34 Volts	2.8 Amps	43.2 Volts	2.9 Amps

Data Collection

As discussed in chapter 2, weather parameters have strong and different roles in affecting the soiling level. Therefore, a weather station was installed on the rooftop to track the weather parameters. Anemometer was used to record the wind speed and direction. Pyranometer and reference cell were used to measure the solar irradiance. Other weather parameters were also recorded like ambient temperature, relative humidity, and rainfall readings.

To continuously collect the data, a CR1000 data logger and a multiplexer were used to record all the Isc readings, weather parameters, along with the module temperature readings (see figure 3.2). The data logger cannot sense directly the current readings; they need to be in the form of voltage readings.

Therefore, Empro MLA-5-50 current shunts were used to convert every current reading to its corresponding voltage reading with a predetermined conversion ratio.

Figure 3.2 CR1000 data logger used for data collection

Each module was connected to a current shunt, resulting in connecting 24 current shunts to the data logger. All the weather sensors were also connected to the data logger. The remaining 12 channels of the data logger were then filled with 12 temperature readings of 12 selected modules as shown in figure 3.3. The numbering system of modules used in figure 3.3 is to be followed in the rest of this chapter and in the following chapters. After wiring up the data logger, it was programmed to record all the data every 1 minute. The table in which the recorded data was generated was also designed in an easy to read manner.

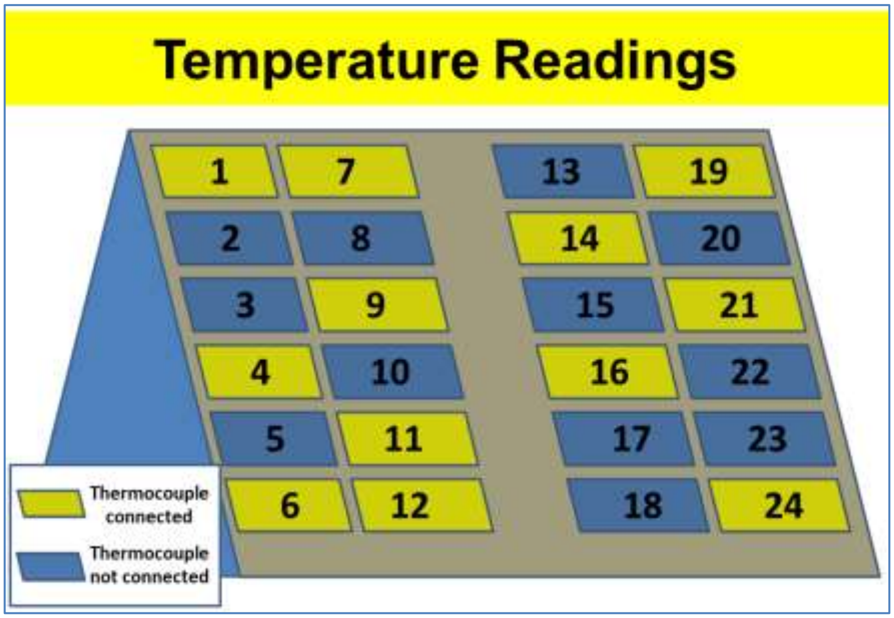


Figure 3.3 Module temperature readings

Project Plan

The whole setup of the project was completed before May 2014. Out of the 24, 17 modules were planned to be exposed to the natural atmosphere with different exposure times (ET), ranging from 1 month to 12 months (figure 3.4) Different exposure times means different soiling levels and also means different cleaning frequencies. Module 2 was not collecting data, while the remaining 6 modules were left for other research purposes like reflectance measurements, studying the dust storm or rain effect on soiling, and AOI studies.

Modules 11 and 12 were assigned for the soiling monitoring study. Soiling loss calculation, AOI study, reflectance, and dust sampling were obtained from all the modules with different exposure times. The detailed project plan can be seen in Appendix A. In this thesis, the first 3 months of the project plan were achieved, while the remaining months are left to be carried out by another thesis. One part of the project is not mentioned in the project plan. In that part, the spatial variation of the soiling effect for the 24 modules was investigated after almost two months of exposure before May 2014.

Data Processing and Analysis

Different Excel worksheets have been developed to process the data collected from the rooftop setup. All the Isc data were STC translated to enable impartial comparison of the Isc readings before and after cleaning. For the soiling monitoring, short circuit current readings for module 11, which was left soiled, and for module 12, which was cleaned weekly, were compared after the STC translation to obtain the monthly soiling loss and the typical average daily soiling rate (soiling loss per day).

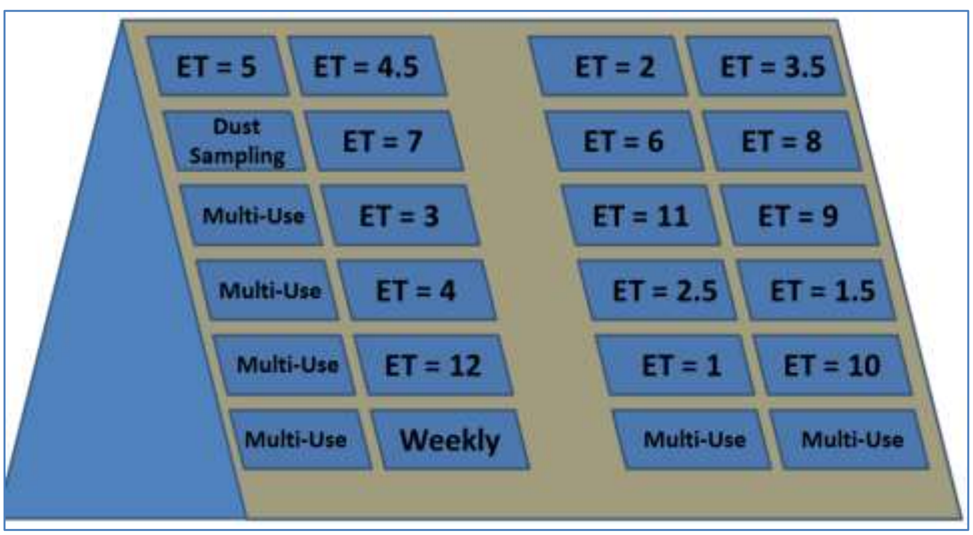


Figure 3.4 The assigned Exposure Time (ET) for the system modules

All the weather data was collected and organized in a way that shows the daily and weekly variations in the climate. That helps in the Climatological Relevance (CR) analysis. CR analysis was an important tool to enable understanding the effect of the weather parameters on the soiling process. The selected weather parameters considered in the CR analysis were air temperature, module temperature, Relative Humidity (RH), and wind speed.

The Angle Of Incidence (AOI) study was conducted by first collecting the Isc readings for the test module before and after the cleaning, and then processing the data using an online tool and a special Excel worksheet. The generated current throughout half a day was collected when the module was soiled before the cleaning, and for the same module, the generated current was again collected for half-a-day period while the module was clean. The half-a-day period could be the first half of the day, from morning to noon, or the second half, from noon to sunset. All the Isc data was collected in a clear sky to ensure simulating typical days without clouds.

The Isc data for the module before and after cleaning were compared, for the same AOI, to obtain the soiling loss as a function of the AOI. Since different AOIs mean different times of the day, the results covered the soiling loss variations along the day. The AOI calculations were done using two online tools named “Local to solar time calculator” and “Sun angle calculator”. Those tools are available from a website named “Power from the Sun.” The website address is www.powerfromthesun.net.

Two main changes of the project plan occurred after running the experiment. The irradiance readings were taken from module 9 instead of the reference cell and pyrometer. Also, the data of dust sampling and reflectance were not presented in the results of the study because they have not collected properly.

Project Flow Chart

The flow chart used to approach the research goals of this project is shown in figure 3.5. The orange squares are the main research processes, the yellow ones are sub processes, and the green ones are input/output data. Financial analysis was the final process that studied the financial impact of the different cleaning frequencies. The results were presented in three charts: Cleaning cost versus Restored annual energy Price (CRP), Financial Loss (FL), and Cleaning Justification (CJ). Details of those charts will be presented in the next chapter.

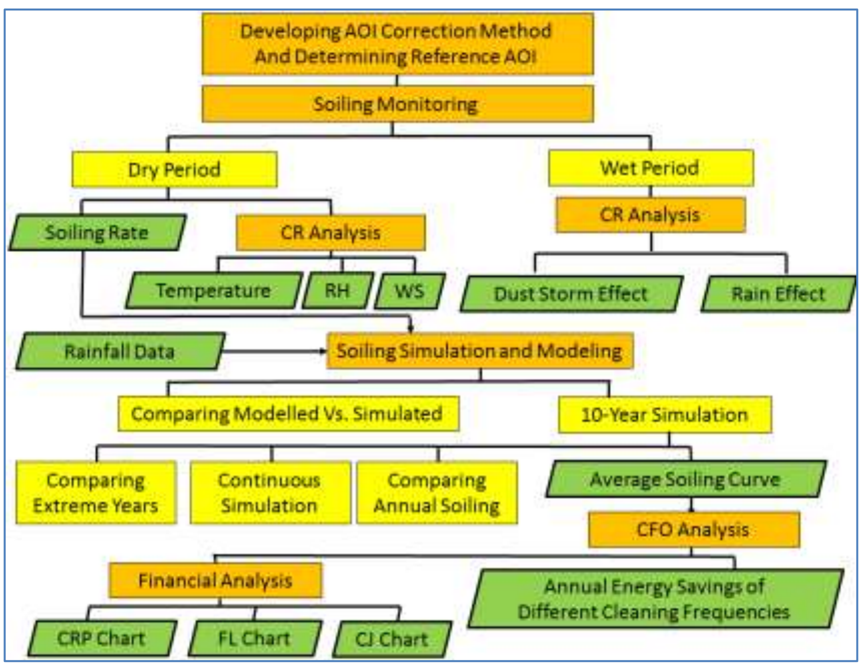


Figure 3.5 The Project flowchart

Before the financial analysis, Cleaning Frequency Optimization (CFO) analysis was conducted to obtain the annual energy savings that could be gained from different cleaning frequencies. To be able to conduct the CFO analysis, the average annual soiling curve had to be obtained. As shown above, the average soiling curve was obtained after simulating the annual soiling curves of the past 10 years. All that was needed for the soiling simulation was to figure out the daily soiling rate of the study location and the record of the rainfalls of the same location. The daily soiling rate was obtained from the soiling loss monitoring in the dry period of the study. Soiling monitoring took place in two different periods: dry and wet. The dry, here, means the period in which no rainfall occurred, while the wet period is the period that had multiple rainfall events. Soiling loss results in the two different periods were correlated with the readings of the weather sensors, revealing some of the climatological relevance to the soiling loss. All of those results were obtained from the Climatological Relevance (CR) analysis.

As shown in figure 3.5, a major part of the project was based on results that had come out of the soiling monitoring. Soiling loss was monitored for the three months of the experiment. The soiling loss was obtained in different days and at different times in those days. As the soiling loss extent is influenced from one time of a day to another, i.e. from an AOI to another, developing a method of AOI correction of the soiling loss for a single AOI was important in this project in order to have comparable soiling loss readings. After studying the relationship between soiling and AOI, figure 3.6 was generated and used in correcting the AOI for all the soiling loss readings. The figure shows that if the soiling loss was 1% at the AOI of 8.9°, it would be almost 1.5% and 2% at the AOIs of 40° and 57°, respectively. AOI of 40° was chosen as the reference AOI for all the soiling loss. Also, AM 1.5 and energy generations are typically around 40^{o} AOI and it can be considered as the reference angle for the normalization of AOI influences. For example, if the measurement of the soiling loss happened at noon (e.g. AOI of 28°) or later on (e.g. AOI of 30°), all of those measurements would be converted as if they have been measured on an AOI of 40°. Choosing AOI of 40° was based on seeing it as a good representative AOI for the average daily soiling loss.

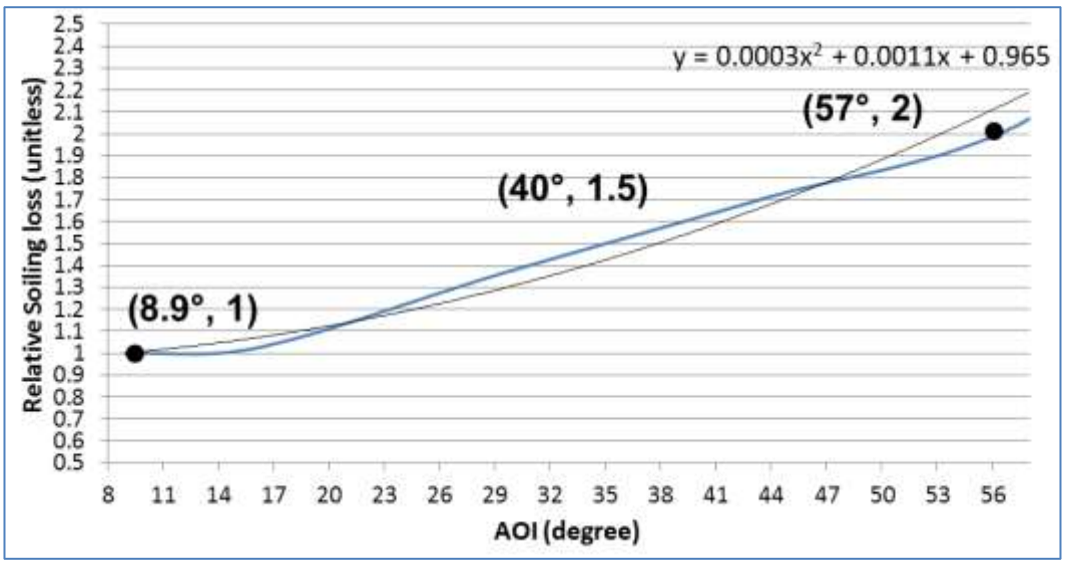


Figure 3.6 AOI correction method used in obtaining the soiling loss

Summary

In order to simulate the real PV installations, twenty four modules were mounted on a mock rooftop located in the outdoor testing area at ASU-PRL. They were left exposed to natural soiling and then cleaned on different cycles. Using weather station and CR1000 data logger helped in recording the performance of each module and the corresponding weather conditions including irradiance, wind, temperature, humidity, and rainfalls. The project plan was briefly presented in this chapter, and deliberately presented in Appendix A. The methods followed for data processing and analysis were also described. In the last section of this chapter, the project flowchart was presented, showing the sequence of the main processes and results of the project.

4- RESULTS AND DISCUSSION

Introduction

Detailed soiling study was performed on the PV modules mounted on the mock rooftop located in the outdoor testing field of the ASU-PRL. The performance of the PV modules, in terms of short circuit currents, was continuously monitored, recorded, and analyzed for a period of three months, May 2014 to July 2014. The soiling studies included soiling monitoring, Climatological Relevance (CR) analysis, AOI studies, soiling simulation and modeling, and cleaning frequency optimization.

Soiling monitoring basically investigates the progress of the soiling loss over time. Obtaining the soiling rates out of the soiling monitoring is of a great importance, characterizing the soiling problem in the given location for different time periods of the year. Additionally, the daily soiling rates are considered the main input for the soiling simulation. Climatological parameters, like rainfall, dust storms, wind speed, and relative humidity, have an obvious influence on the soiling process. Therefore, CR analysis was important to be conducted along with the soiling monitoring. AOI study investigates the variations of the soiling loss along the day. Soiling simulation is a useful tool to enable estimating the annual soiling loss for a given location, and it is important in determining the cleaning frequency needed for the PV arrays. In this chapter, the results of all above-mentioned studies will be presented and discussed. In addition to that, the next section will discuss the results of the initial soiling measurements of the PV modules taken after the last cleaning before starting the study. Those measurements were taken to show the difference in the soiling losses among the 24 PV modules of the mock rooftop.

Spatial Variation of the Soiling Effect

The main soiling study started on May 1st, 2014. All the 24 PV modules were cleaned just the day before the starting date. Before then, the last time the modules were cleaned was almost two months ago. That means before running the study, the PV modules got soiled for an exposure period of almost two months. Obtaining the soiling losses for the PV modules was important in order to identify the variations in the soiling losses among the PV modules.

All the Isc data before and after the cleaning were collected by the data logger. An obvious variation of the soiling effect was noticed among the PV modules. Figure 4.1 shows the soiling loss for each PV module on the mock rooftop. Unlike other parts of this report, the soiling loss percentages were presented without the negative sign for sake of simplicity. Out of 24 modules, 16 modules had a soiling loss that falls in a 3-4% range, 4 modules with a 4-5% soiling loss, and the other 4 modules with a 5-6% soiling loss. Thus, it was noticed that the modules that were mounted close to the ground and sides had higher soiling loss than the other modules that were closer to the center. That shows that soiling loss was not distributed evenly between the 24 modules. Higher soiling losses in the modules close to the ground and sides could be reasoned by the fact that those modules are close to the human activity in the lab, along with the proximity to the sand-covered floor that surrounds the mock rooftop. Though not investigated, wind direction is expected, also, to play a role in causing the soiling non-uniformity among the PV modules.

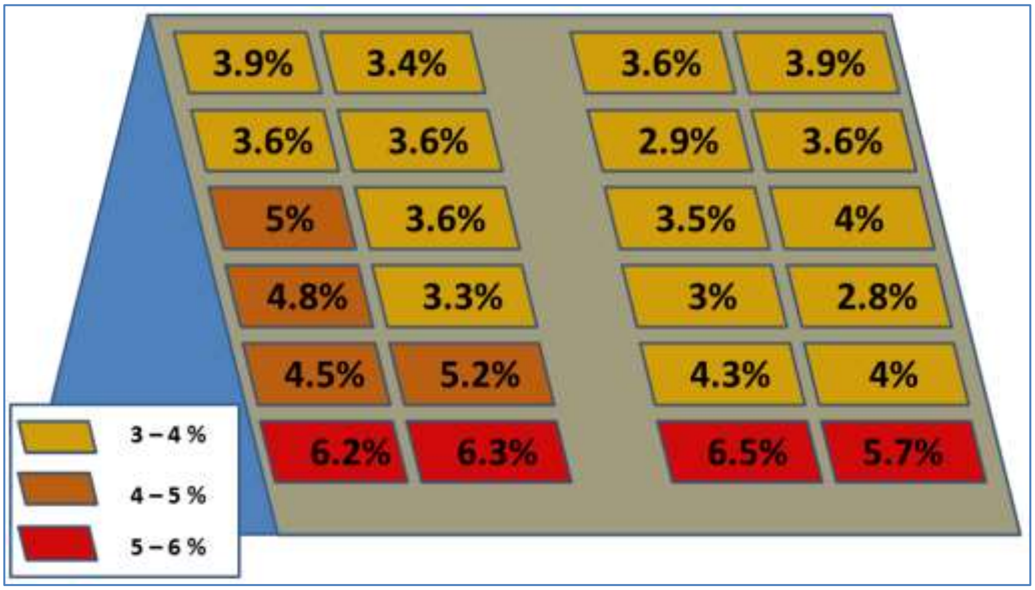


Figure 4.1 Soiling loss distribution after almost 2 months of exposure (March and April, 2014)

It needs to be known that the soiling loss of the module 2 was assumed to be 3.6% as seen in the figure. The reason the assumption was taken is that the data logger was not able to collect the data for module 2. Therefore, 3.6% was assumed as it is equal to the soiling loss of module 8, which was just next to module 2. Table 4.1 shows some statistical figures related to the soiling loss distribution of the 24 PV modules of the mock rooftop.

Table 4.1

Statistics for the soiling loss distribution in the mock rooftop

Average soiling loss	4.2%
Median	3.9%
Mode	3.6%
Standard deviation	1.1

Results of Soiling Monitoring and CR Analysis

The performance, in terms of Isc, of two PV modules was monitored over three months, May to July 2014. As shown in figure 4.2, the two modules used in the soiling monitoring study were modules 11 and 12. Module 11 was kept without cleaning, while module 12 was cleaned in different periods. By comparing the performance of the two modules, the soiling loss of module 11 was obtained over the three months of the experiment. All weather data was collected and sorted for the different periods of the experiment.

Figure 4.2 The two modules used in the soiling monitoring

In the data analysis, the three-month experiment was divided into 16 periods. Table 4.2 shows the duration of each period, the weather conditions during the period, and the level of the cleanness of the module during which the weather events occurred.

Table 4.2

Different periods used in the data analysis of the soiling monitoring

Period	Duration	Weather Condition	Module Condition
1	Day1-Day7	Dry	Dirty
2	Day8-Day14	Dry	Dirty
3	Day15-Day21	Dry	Dirty
4	Day22-Day30	Dry	Dirty
5	Day31-Day35	Dry	Dirty
6	Day36-Day42	Dry	Dirty
7	Day43-Day49	Dry	Dirty
8	Day50-Day56	Dry	Dirty
9	Day57-Day63	Dry	Dirty
10	Day64-Day72	Light Rain	Dirty
11	Day73-Day75	Heavy Rain (0.52 in.)	Dirty
12	Day76-Day79	Light Rain	Clean
13	Day80-Day84	Dry	Clean
14	Day85-Day87	Light Rain	Clean
15	Day88	Dust Storm W/ Light Rain	Clean
16	Day89-Day91	Light Rain	Dirty

Breaking down duration of the experiment into different periods was important in order to investigate the climatological relevance to the dust accumulation/removal by which soiling increases/decreases, respectively. From period 1 to period 9, the modules went through dry summer where there were no rainfalls. After period 9, the monsoon (wet) season started where the modules were exposed to multiple rainfall events and dust storms. Knowing whether the module was clean or dirty, is also important in order to distinguish the rainfall effect on the soiling both situations.

During the dry season (periods1-9), except periods 7 and 9, soiling loss kept increasing, which was represented by obtaining more negativity in the soiling loss percentage (see figure 4.3). On day 72, light rain occurred, decreasing the soiling loss from -3.82% (in day 63) to -2.29%, which is equivalent to cleaning the module with a percentage of 39.98%. The heavy rain of 0.52in (occurring on day 75) fully cleaned the PV module. Light rainfall (non-sensible by rain sensor) occurrence on the clean module, like what happened in day 79, however, caused an increase of the soiling loss, as that light rain drops were carrying dust. On the other hand, a sudden increase in the soiling loss occurred on day 88 due to the incidence of a dust storm. Since the module got dirty after the dust storm, the following light rain in day 91 acted as a cleaning agent, decreasing the soiling loss.

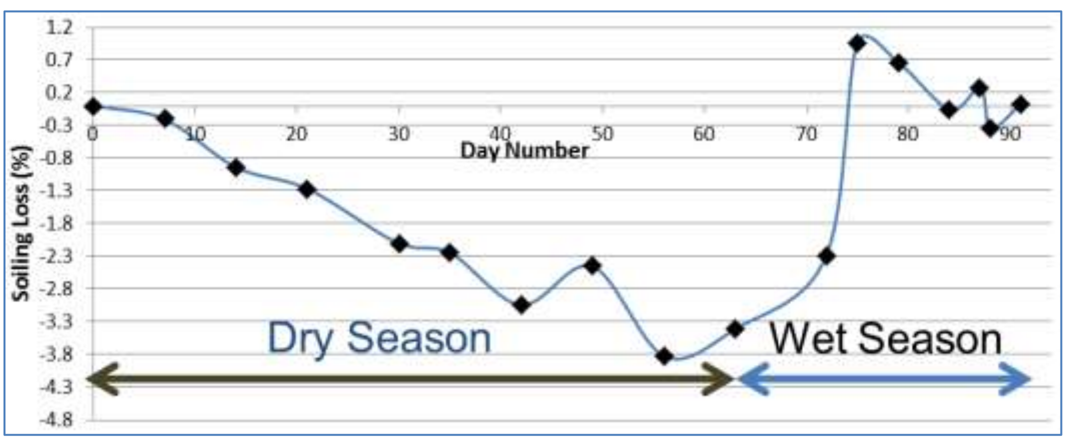


Figure 4.3 Soiling monitoring for 91 days, May to July 2014

Most of the 16 periods of the experiment were 7-day periods. However, some of the periods had different number of days like 9, 3, and 2 days. To enable comparing between periods, normalized soiling rates were generated for each period, by dividing the soiling loss in that period by the number of days of the period. The normalized daily soiling rates of the 16 periods are tabled in table 4.3 and depicted in figure 4.4.

Table 4.3

Normalized soiling rates of the 16 periods of the experiment

Period	Normalized soiling rates	Weather event
1	-0.028	---
2	-0.10547	---
3	-0.04873	---
4	-0.0914	---
5	-0.03	---
6	-0.11306	---
7	+0.084603	---
8	-0.19673	---
9	+0.059996	---
10	+1.11039	Light rain
11	+3.263934	Heavy rain
12	-0.30386	Light rain
13	-0.14275	---
14	+0.109236	---
15	-0.61569	Dust storm w/ light rain
16	+0.370958	Light rain

After obtaining the soiling rate for each period, weather-related data was also sorted for the 16 periods (see figure 4.5). Those data included the ambient and module temperatures, wind speed, and relative humidity. Looking at figure 4.5, the general pattern of the weather-related data can be noticed. Module temperature was influenced by the ambient temperatures, and both of them had higher average values in the wet season than the case in the dry season. As expected, since the monsoon season has a higher frequency of rainfalls, relative humidity was higher in the monsoon season than the dry season. On the other hand, wind speed was showing a fluctuating trend during the 16 periods of the experiment, with a noticeable increase during the dust event in period 15.

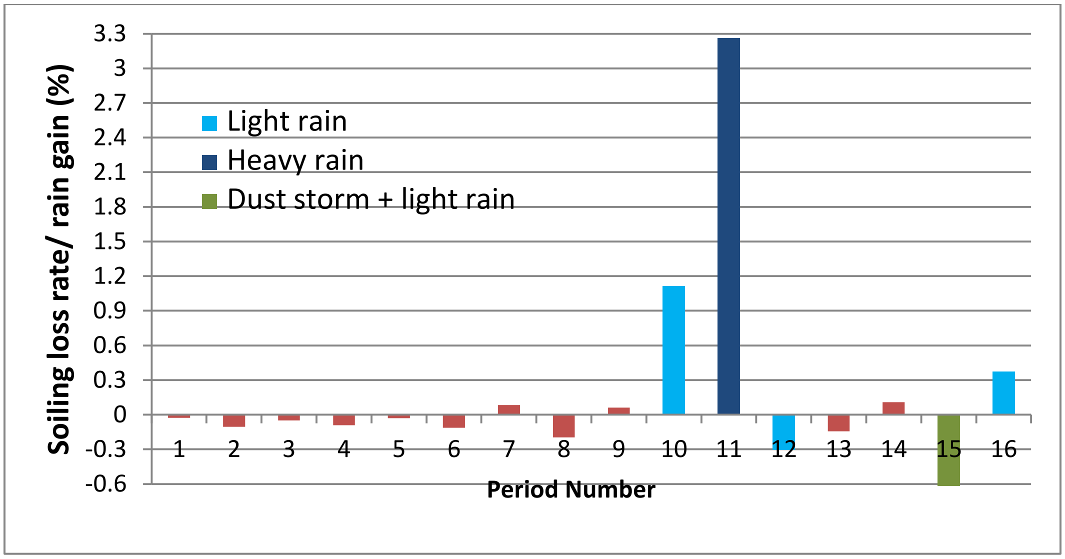


Figure 4.4 Normalized soiling rates of the 16 periods of the experiment

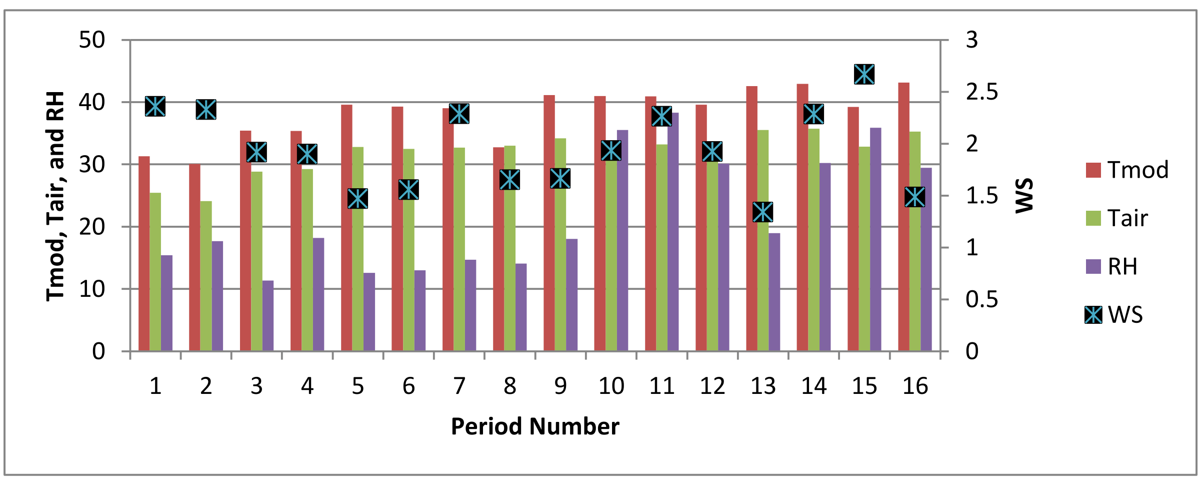
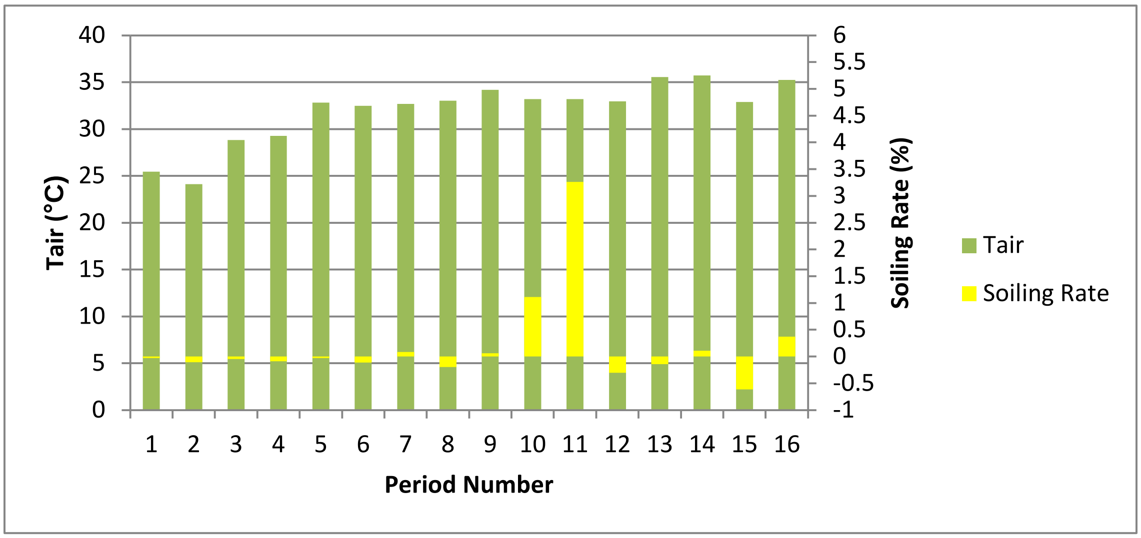
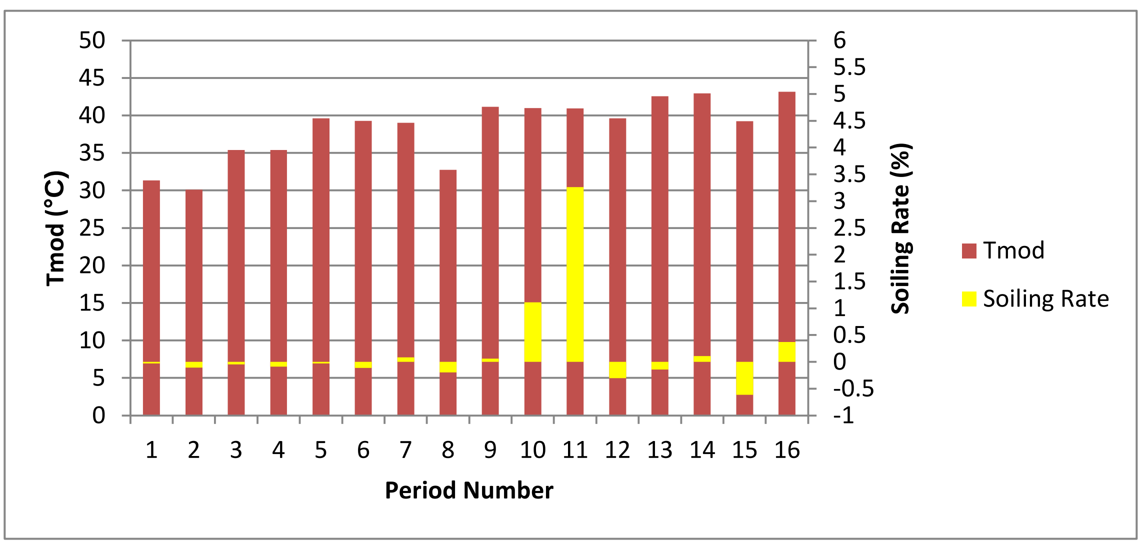


Figure 4.5 Weather-related data for the 16 periods of the experiment

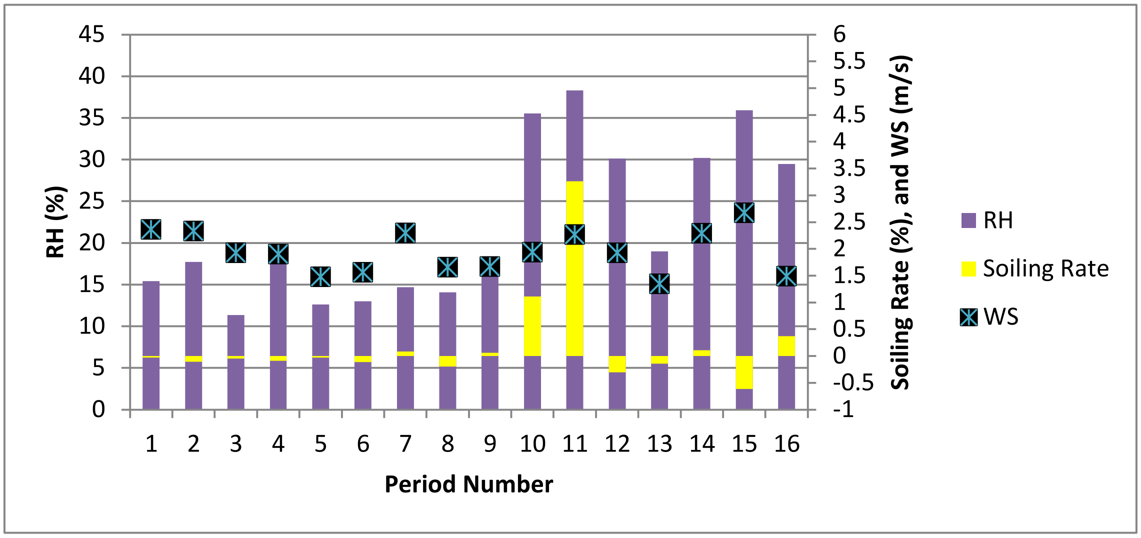
To easily correlate the weather-related data with the soiling data, three more bar charts were generated, showing the normalized soiling rates for each period, along with the corresponding weather data of the same period (figure 4.6). Figures 4.6 (a) and (b) show the independency of the soiling rate from the ambient and module temperatures. On the other hand, wind speed and relative humidity seemed to have a direct influence on the soiling rates (figure 4.6 (c)).



(a)



(b)



(c)

Figure 4.6 Soiling and weather data for the 16 periods of the experiment: (a) soiling versus air temperature, (b) soiling versus module temperature, (c) soiling versus wind speed and relative humidity

To narrow down the major influential factors from the weather data on the soiling rate, another chart was generated with an exclusion of the module and ambient temperatures (figure 4.7). Investigating the effect of the wind speed (WS) and relative humidity (RH) on the soiling rate was done only in the dry period of the study; since the dry period represents the normal range of the WS and RH. The wet period could not be used because it had dust and rain events, which represents special cases of WS and RH, respectively.

From periods 1 to 9, two main conclusions were drawn. First, it was noticed that as the relative humidity (RH) increases, soiling rate increases. Referring back to figure 4.6 (c), it was noticed that all odd periods (1, 3, 5, and 7) had lower soiling rates than the even periods (2, 4, 6, and 8). RH could be easily linked with that comparison, as all the even periods had high average RH values.

As seen in figure 4.8, when the wind speeds were almost the same in the three left bars, the increased RH in periods 6 and 8 led to an increased soiling rates during those periods compared to the soiling rate during period 5.

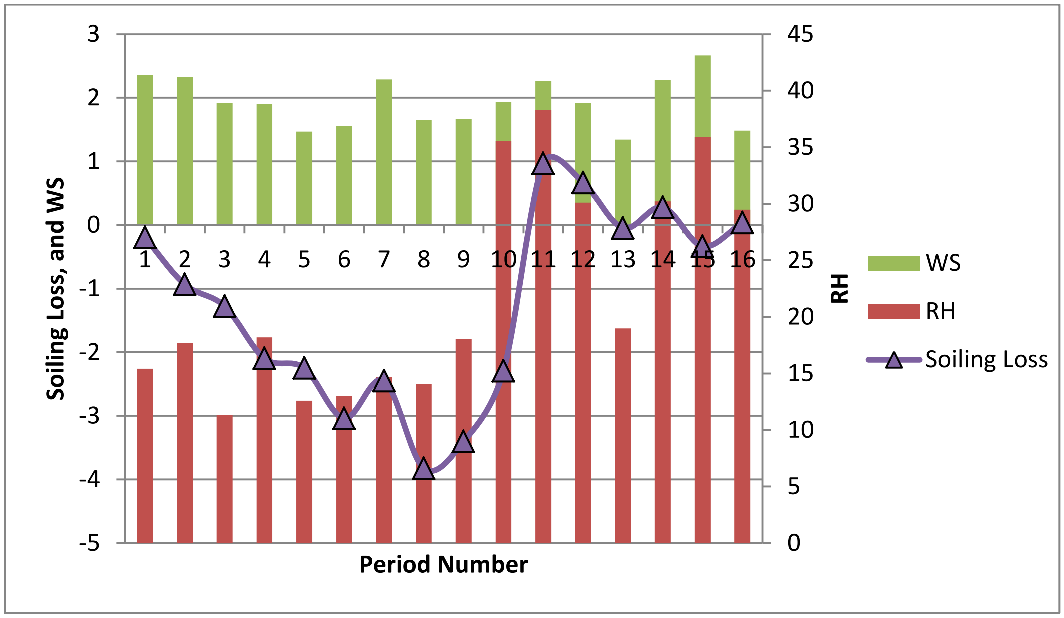


Figure 4.7 Soiling, wind speed, and relative humidity data for the 16 periods of the experiment

The second notice from the dry period was that as wind speed increases, soiling rate decreases. Again form figure 4.8, when the relative humidity values in periods 7 and 8 were almost the same, the increased wind speed in period 7 led to a decreased soiling rate during period 7 compared to the soiling rate obtained during period 8. Thus, relatively high winds could work as natural cleaning agents.

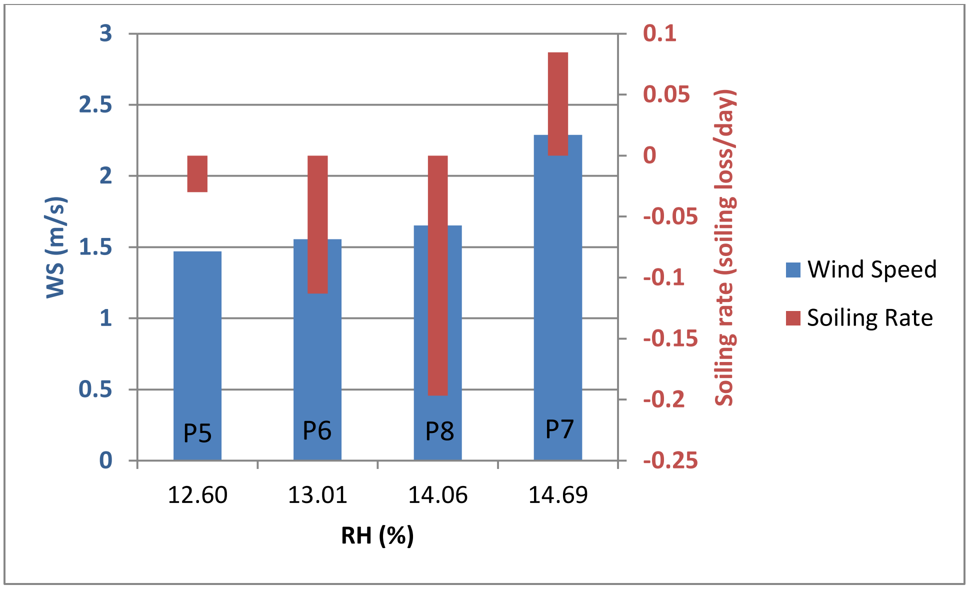


Figure 4.8 The effect of relative humidity and wind speed on soiling

The effect of high winds gets even higher when they stay for multiple consecutive days. This was proven in period 7, where high peaks for the daily wind speeds were repeatedly happened (figure 4.9). However, high winds may not be a cleaning agent like what happened in period 15 in which high winds occurred in the dust storm, carrying dust and, in turn, increasing soiling. To see the detailed (every minute) RH and WS readings for all the periods of the experiment, refer to Appendix B. Tracking those detailed readings can give a very conclusive picture about the effect of the RH and WS on soiling.

From the above findings, it is concluded that in dry periods, high relative humidity causes higher soiling rate. However, this relationship is also influenced by the level of the wind speed. High wind speeds, except during a dust storm, counteract the effect of the high relative humidity. This is because the fact that daily peak of wind speeds was found to occur at the same time of the daily minimum of the relative humidity. This illustrates the fact that high winds easily move the dust particles since those particles do not contain high moisture, which make thems less dense and more vulnerable to be carried away with winds. Figure 4.10 shows an example from three days of the experiment, showing how the high winds usually appear during the day in times where the relative humidity is at its minimal values.

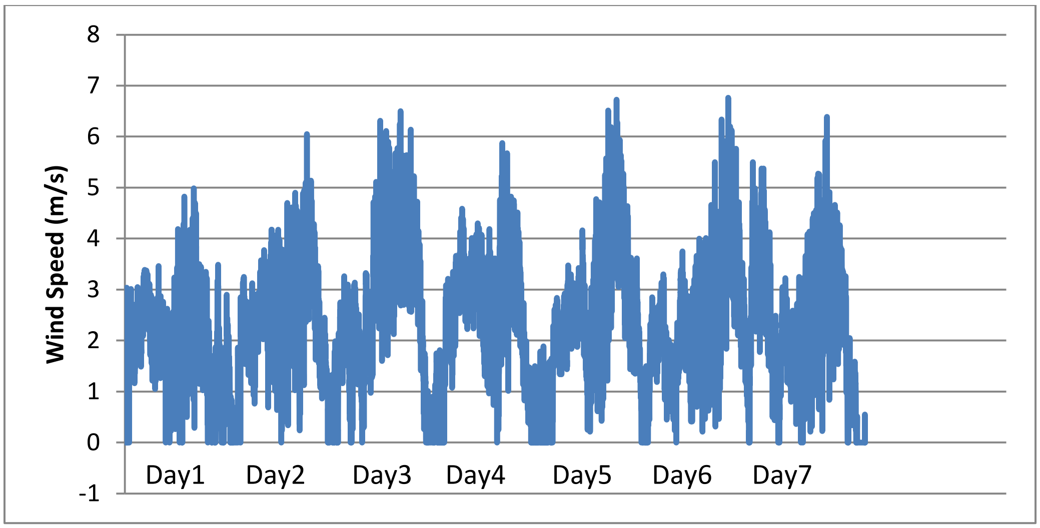


Figure 4.9 High winds for consecutive days in period 7

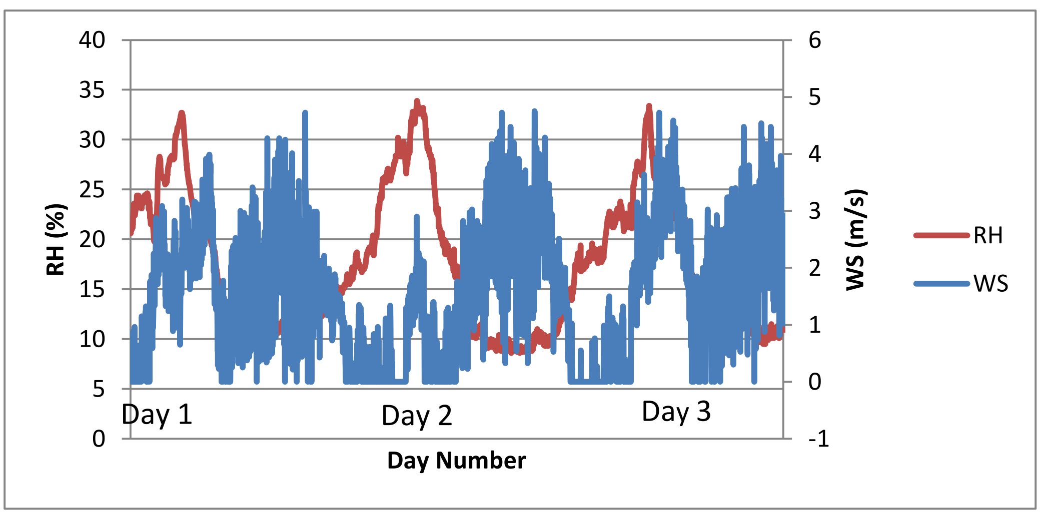


Figure 4.10 Occurrence of high winds along with low relative humidity

The influence of the relative humidity on soiling was further investigated. Figure 4.11 shows an illustration of how the increase of RH could lead to an increase of dust accumulation and in turn an increase of soiling loss. As relative humidity increases, the aerosols get heavier, increasing their falling rates onto the PV modules due to the increase of the gravitational force. Once the dust particles were deposited on the surface of the solar module, the water content of those particles forms a bonding force between the particles and the surface of the PV module. When it gets dry later, more particle adhesion will be a result of the cementation process. Figure 4.12 shows a graphic illustration of the cementation process, in which the fallen particles get strongly bonded to the surface as a result of experiencing high humidity followed by very low humidity (Sarver, Al-Qaraghuli, and Kazmerski, 2013).

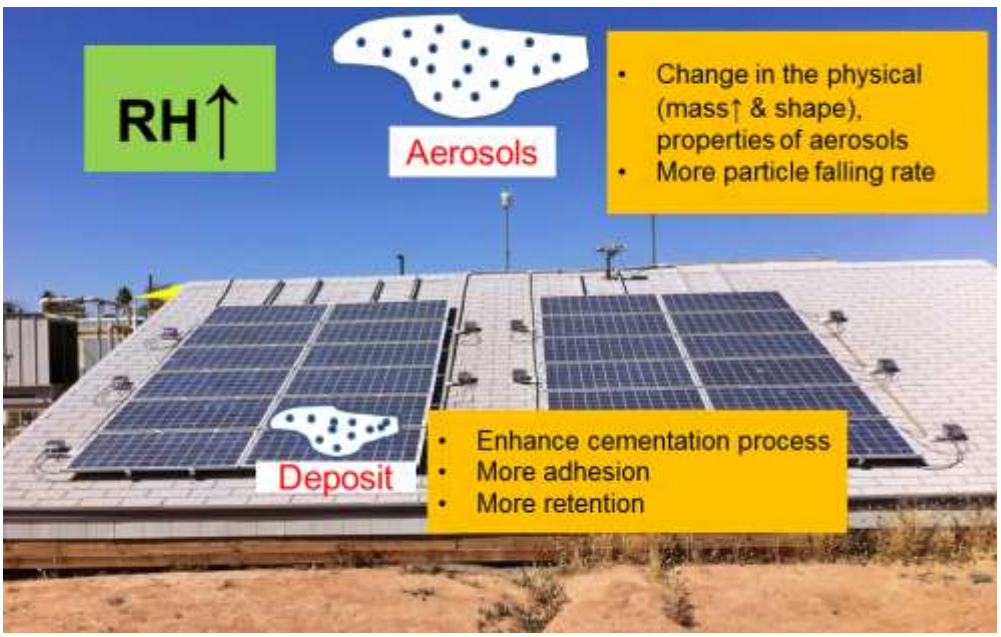


Figure 4.11 Relative humidity effect on soiling (Sarver et al., 2013).

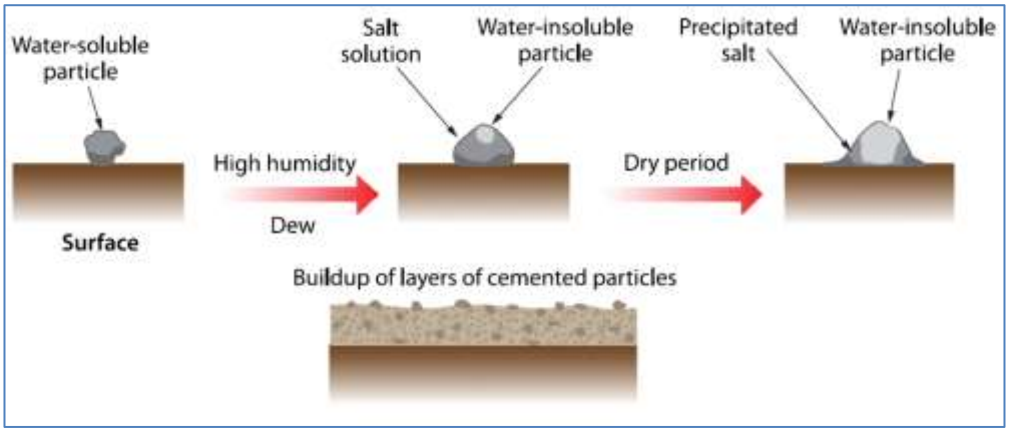


Figure 4.12   The cementation process (Sarver et al., 2013)

Other results out of the soiling monitoring included the monthly soiling loss for the three months of the experiment. Figure 4.13 shows the approximate soiling loss for the three months of the experiment. The first two months were parts of the dry summer period. The soiling rates in May and June were obtained as -2.1% and -1.31%, respectively. On the other hand, the soiling rate considerably decreased to almost (+1.34%) in July due to the multiple rainfall events which occurred in that month.

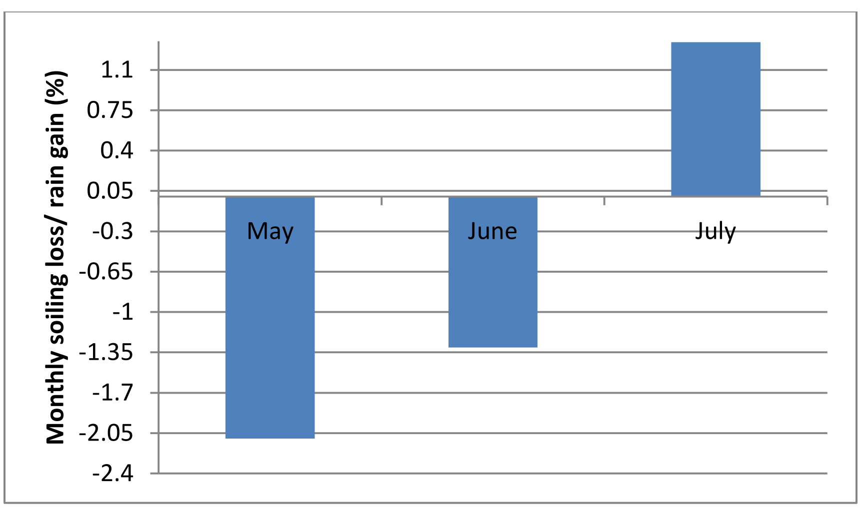


Figure 4.13   The monthly soiling loss for the three months of the experiment

Since the daily soiling rate in the dry summer season is needed for soiling simulation, it was obtained from the monitored soiling curve of the dry season. The 3rd period was chosen because it was found as a closest period to the trend line of the soiling loss during the dry season. In the 3rd period, the soiling loss reached -1.27542%. Dividing the latter by 21 days (that corresponds to the 3rd period), the daily soiling rate was found as -0.061%.

AOI Dependence of the Soiling Loss

Soiling loss varies as the Angle Of Incidence (AOI) changes along the day. To investigate that in a quantitative sense, the performance of the PV modules was compared throughout the day, before and after cleaning. Three different soiling levels were studied: light, medium, and heavy soiling. Figure 4.14 shows the soiling loss as a function of AOI for those three soiling levels. For an AOI range of 16° to 73°, the soiling loss varies from -0.87% to -1.19% in light soiling, -1.79% to -4.96% in medium soiling, and -3.14% to -8.64% in heavy soiling. Figure 4.14 shows that as the soiling level increases, the variation range of the soiling loss throughout the day gets wider. In the light soiling level, the variation range of the soiling loss was 0.32%, while in the medium and heavy soiling levels it reached 3.17%, and 5.5%, respectively (see table 4.4).

The nature of the varying soiling loss along the day is an important factor to consider in the accurate modelling and simulation of the soiling problem. Measuring the soiling loss at noon gives different numbers from the afternoon measurement, for example. In the soiling monitoring, a reference AOI must be chosen in order to compare the daily/monthly soiling rates. In the soiling simulation, the best way to simulate the soiling loss is to integrate the different soiling losses along the day for different AOIs, and obtain the sum as a daily soiling loss. Applying that in the three cases of the study, the daily soiling loss for lightly soiled module is -0.95%, for medium soiled module is -3.13%, and for heavily soiled module is -5.3%.

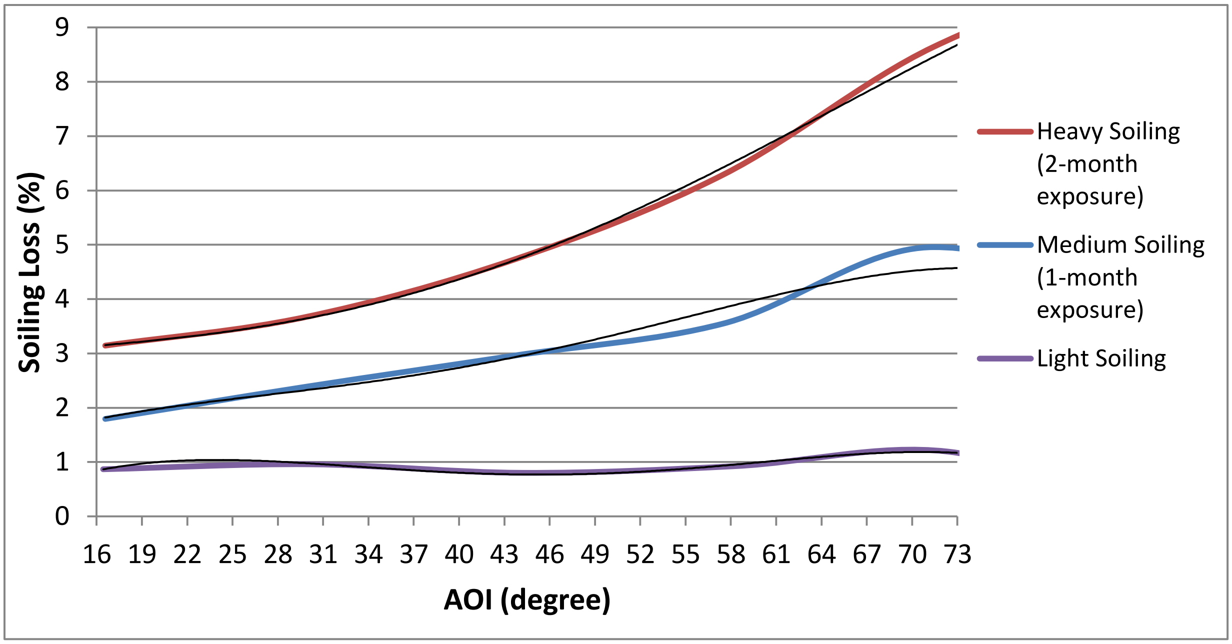


Figure 4.14 AOI dependence of soiling loss

Table 4.4

Soiling loss versus AOI for three levels of soiling

Light Soiling		Medium Soiling		Heavy Soiling	
AOI	Soiling Loss (%)	AOI	Soiling Loss (%)	AOI	Soiling Loss (%)
16.43	-0.868315	16.57	-1.794777	17.33	-3.144014
30.14	-0.959864	29.76	-2.38231	30.14	-3.665625
44.21	-0.802084	43.58	-2.957357	43.76	-4.72165
58.31	-0.925803	57.51	-3.55062	57.55	-6.293242
72.34	-1.193752	71.39	-4.956367	72.91	-8.638821

Soiling Simulation

To optimize the cleaning frequency of PV modules, or to justify the PV cleaning, soiling simulation and financial analysis should be performed. In soiling simulation, soiling loss for a given location is simulated over a period of time, typically a year. Soiling simulation is based on estimating the soiling loss over time by knowing the average daily soiling rate of a location, besides knowing the weather data records, especially the rainfall data.

From the soiling monitoring data, the average daily soiling rate was obtained as -0.061%. This figure is used as an approximation figure to simulate the real soiling loss happening over time in Mesa, AZ. Figure 4.15 shows the soiling simulation for the period of the soiling monitored, depicting both measured and simulated (estimated) soiling curves. As seen in the figure below, soiling simulation is a good approximation approach to estimate the actual soiling loss.

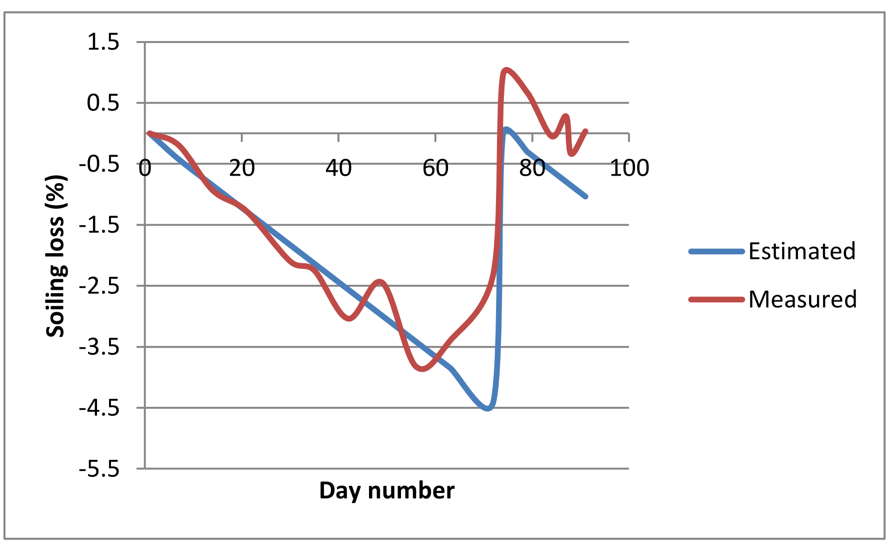
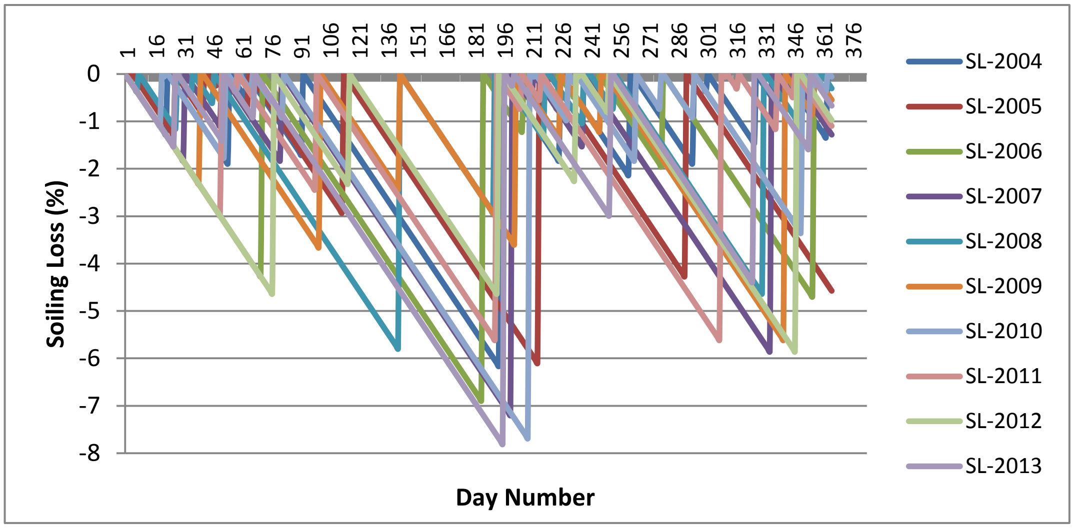
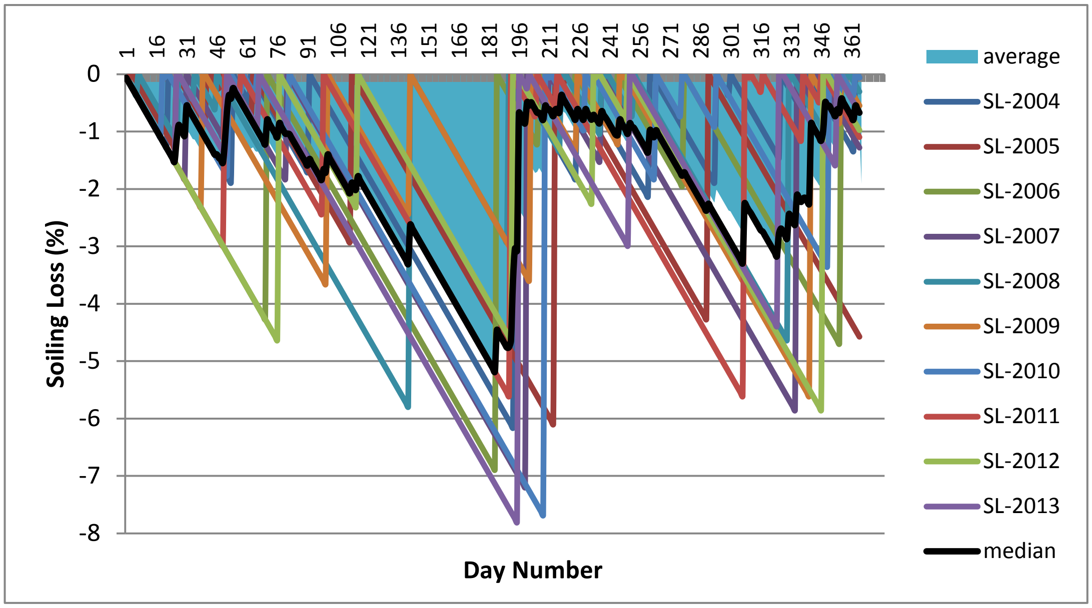


Figure 4.15 The similarity between simulated (estimated) and monitored (measured) soiling

Using the daily soiling rate of -0.061% and rainfall data from AZMET database, soiling simulation was conducted for the last 10 years, 2004 to 2013. The soiling simulation for the 10 years is shown in figure 4.16 (a), and with featuring both median and average soiling curves that were obtained from the family of the ten soiling curves of the ten years (figure 4.16 (b)).



(a)



(b)

Figure 4.16 Soiling simulation: (a) for 2004 to 2013, (b) average soiling curve

The soiling curves of the last ten years were different but they have a common pattern. The average soiling curve suggests that soiling loss reaches high values during two seasons in the year. The first season is the dry summer period from day 82 (March 23rd) till day 215 (August 3rd), where rainfalls are less common than any other periods of the year. The average soiling loss in the summer season was obtained as -2.71%. The second soiling season is during the end of the year from day 253 (September 10th) till day 356 (December 22nd), where the average soiling loss reaches -2.03%.

Though it is rare, in some years there would not be the second season. This is easily seen in figure 4.17, where it shows the soiling curve for the driest and wettest years of the ten studied years. The wettest year was 2004 with an annual average soiling loss of -1.43%, while the driest was 2007 with an average of –2.24%. The significant difference between the two years was in the nature of the period of the end of the year, where 2004 had multiple rainfalls and 2007 had no rain events during most of that period.

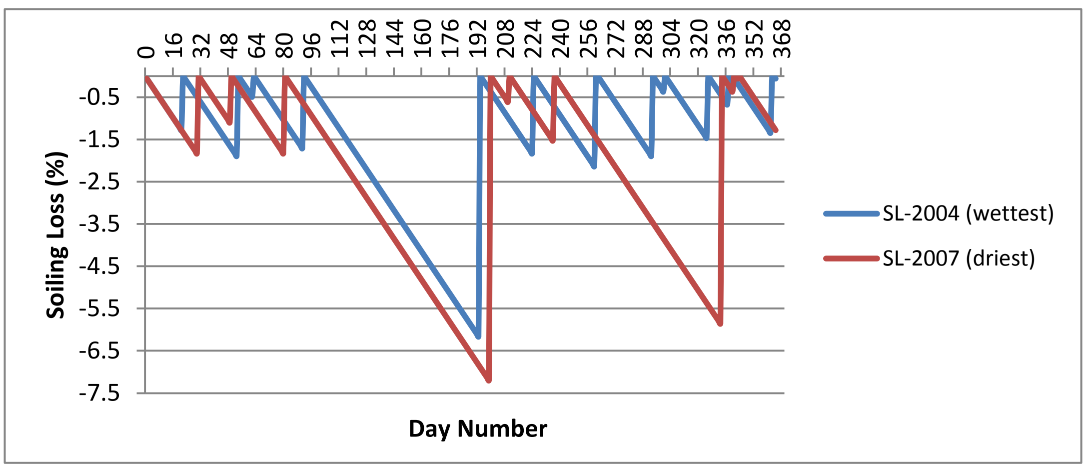


Figure 4.17 Soiling simulation for the driest and wettest years in the past 10 years

Not every year must start with the minimum soiling loss. Some of the years start with a relatively high soiling loss coming from their previous years. Therefore, another way to look at the soiling loss is to see the cumulative effect that may happen from one year to year. That effect was studied through figure 4.18, where all soiling curves were connected to each other in a chronological order to see if higher soiling peaks may appear. It turns out that the possibility of that cumulative effect is almost negligible, as the highest peak was -8.85% which is very close to the highest peak in the individual soiling simulation (-7.81%). As noticed from the figures above, even for the most different years, the soiling loss over the year mostly has a cycle where it starts low in the beginning of the year and ends up low in the end of the year. This fact actually is a main reason of the insignificance of the cumulative effect of the continuous soiling simulation. The average soiling loss of the continuous 10 years was found as -2.04%.

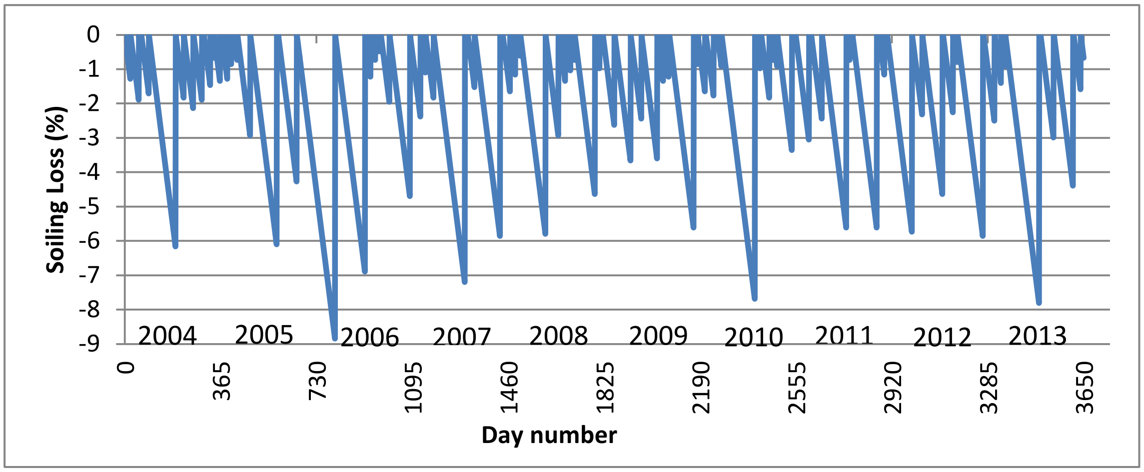


Figure 4.18 Continuous (cumulative) soiling simulation for years 2004 till 2013

The average annual soiling loss percentages of the past ten years were obtained and shown in figure 4.19. The average annual soiling loss was calculated from the ten years and obtained as -1.91%. Additionally, two things were noticed from the figure below. First, there were no large variations in the soiling loss percentages among the different years; only 0.8% difference between the two extreme years. Secondly, there was a pattern of fixed cycle in which the annual soiling loss starts low (2004), gradually increases (2004 to 2007) to reach a high value (2007), and eventually returns to a low value (2008) again. Further investigation in the future needs to be done to validate the presence of such kind of cycles.

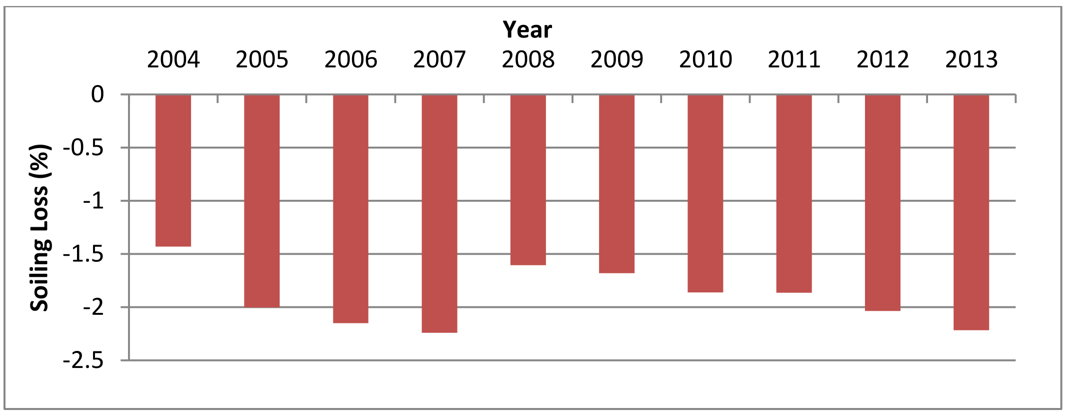


Figure 4.19 Average annual soiling loss for years 2004 till 2013

Cleaning Frequency Optimization

In the previous section, the average soiling curve was obtained out of simulating the soiling loss of the past 10 years. Using the average soiling curve, this section aims to simulate the effect of three cleaning frequencies (CFs) on mitigating the soiling loss throughout the year. Those cleaning frequencies are once a year (CF=1), twice a year (CF=2), and three times a year (CF=3).

Starting with the CF of 1, day 153rd (June 2nd) was found to be a good day to clean the PV modules since that will cut off a big portion of the biggest soiling period (summer period). The overall reduction in the soiling curve after applying a cleaning frequency of one time a year is shown in figure 4.20. With CF=1, the annual average soiling loss (-1.91%) was reduced by 20.3%, cutting -0.39% and resulting in -1.52% as an annual average soiling loss.

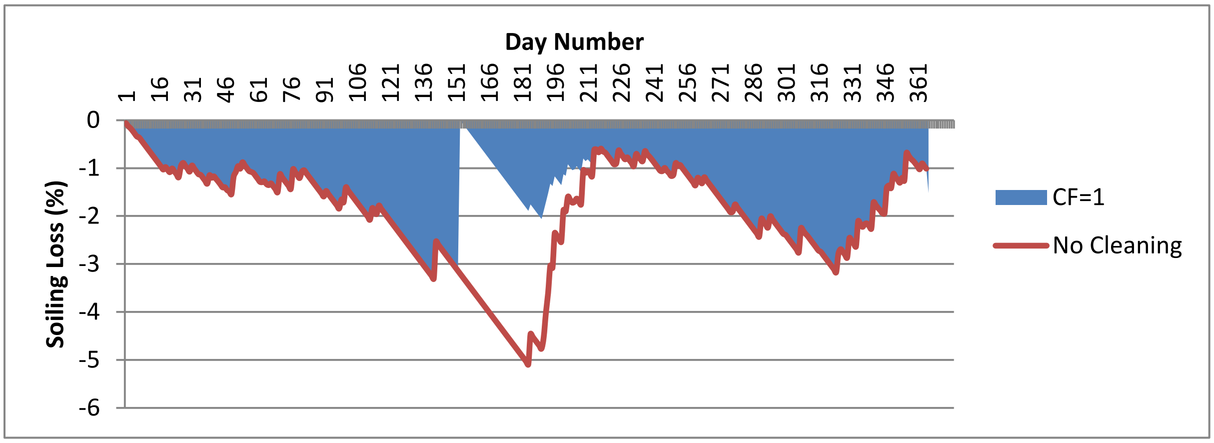


Figure 4.20 The effect of CF=1 on the average soiling curve

In case of CF of 2, days 153 (June 2nd) and 296 (October 23rd) were found to be good days to clean the PV modules as that will cut a considerable portion from both soiling seasons. The overall reduction in the soiling curve after applying CF=2 is shown in figure 4.21. With CF of 2, the annual average soiling loss (-1.91%) was reduced by 30.85%, cutting -0.59% and resulting in -1.32% as an annual average soiling loss.

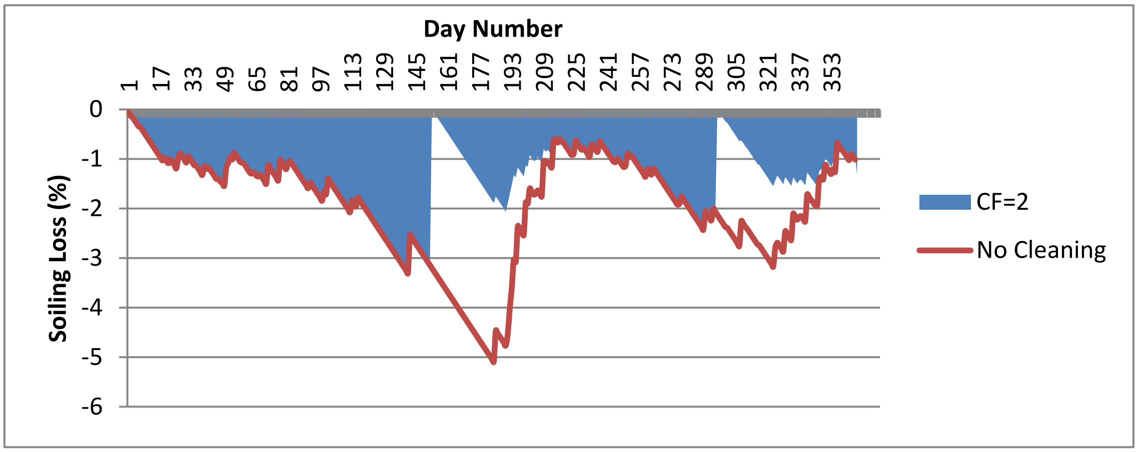


Figure 4.21 The effect of CF=2 on the average soiling curve

Studying CF=3, days 141 (May21st), 163 (June 12th), and 296 (October 23rd) were found to be good days to clean the PV modules so that the soiling loss would be maintained low. The overall reduction in the soiling curve after applying CF=3 is shown in figure 4.22. With CF=3, the annual average soiling loss (-1.91%) was reduced by 37.24%, cutting -0.71% and resulting in -1.2% as an annual average soiling loss.

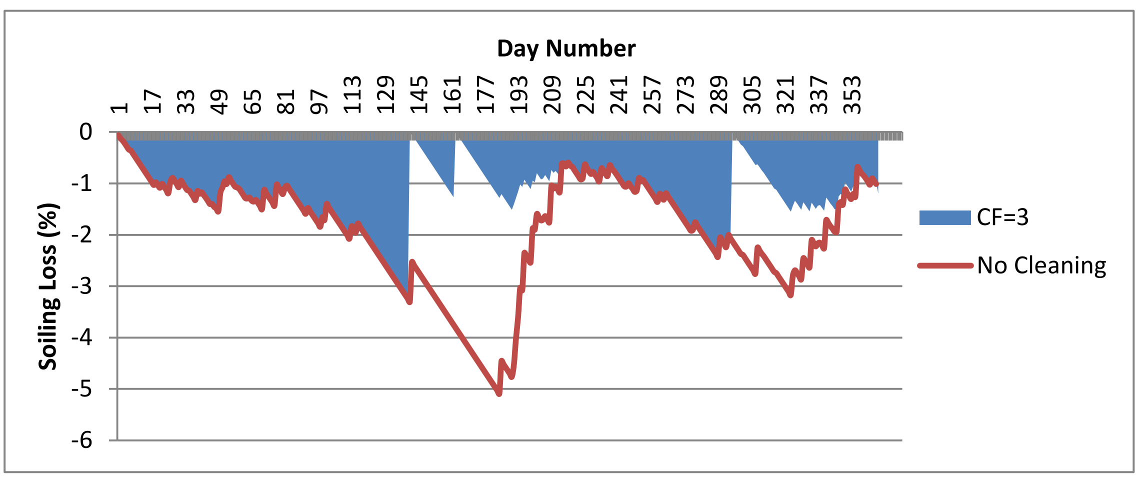


Figure 4.22 The effect of CF=3 on the average soiling curve

Now, after investigating the effect of the three different cleaning frequencies, the annual energy savings, from the different frequencies, is bar charted in figure 4.23. Another way to present that is shown in figure 4.24 where the annual average soiling loss is bar charted in case of no cleaning (CF=0), once a year cleaning (CF=1), twice a year cleaning (CF=2), and three times a year cleaning (CF=3).

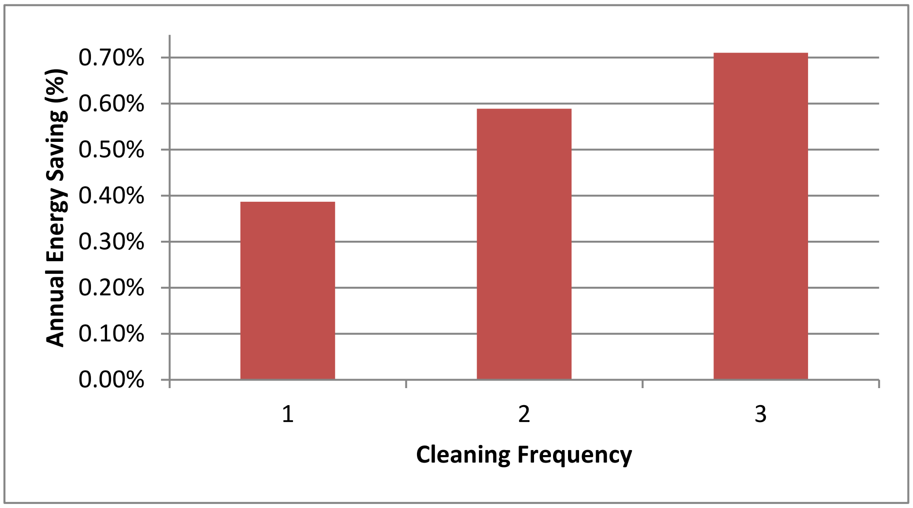


Figure 4.23 The annual energy savings from different cleaning frequencies

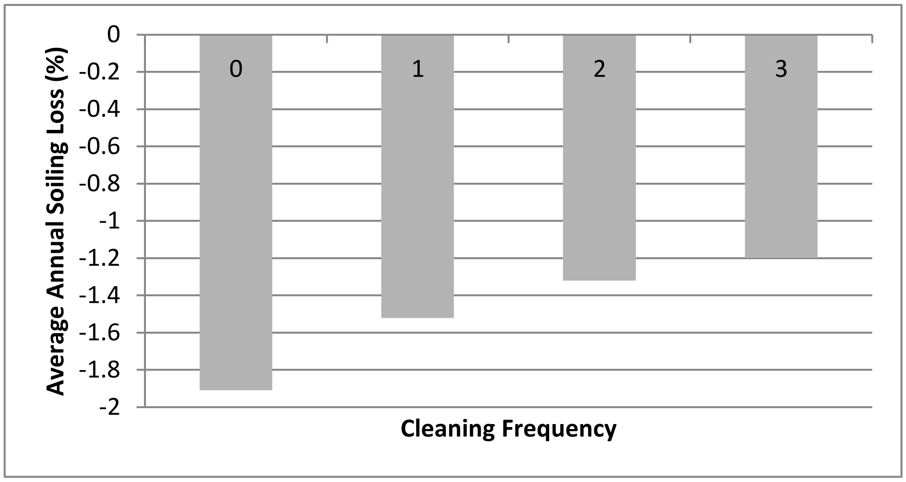


Figure 4.24 The average annual soiling loss for CFs=0,1,2, and 3

Studying the effectiveness of different cleaning frequencies on the annual performance of PV modules has to be done besides the financial analysis in order to justify the economic impact of those cleaning frequencies. Under specific assumptions, the financial analysis, for the different cleaning frequencies, was performed and sorted for residential, commercial, and utility-scale PV applications. For each of those categories, three kinds of charts were generated. The first one depicts Cleaning cost versus Restored annual energy Price (CRP) chart. As a function of system size, this chart shows the cost of different cleaning frequencies and the corresponding economic benefit due to the cleaning. In the second chart, the Financial Loss (FL), for different cleaning frequencies, was shown. The second chart was designed for those who have no choice other than cleaning their PV systems, and they need to quantify the loss to be used later in their economic analysis. The third kind of chart is called Cost Justification (CJ) chart, where the breakeven values, between the cleaning cost and its economic benefit, are charted. Based on the period of 25 years, those charts were generated in order to simulate the known typical lifetime of PV systems. The main goal of the CJ charts is to provide the PV industry a guiding reference of the cost beyond which the PV operators should not invest in cleaning their systems for a 25-year period. Any dollar amount less than the breakeven value is economically justified to be invested in the PV cleaning.

Residential PV systems typically range from 3 to 10 kW. The following assumptions were taken into account in analyzing such systems: the cleaning cost was considered as $2/ PV module, the price of the restored energy was based on

$0.11/kWh tariff (SWEEP, 2014), and 1579 kWh is the annual energy for each 1-kW PV array (based on the NREL's PVWatt® tool). Figure 4.25 shows the CRP chart for the residential PV systems. As can be seen from the latter figure, the cleaning cost is way more than its economic benefit, in all different cleaning frequencies. Therefore, cleaning residential PV systems by hiring a company cannot be justified whatever the system size is.

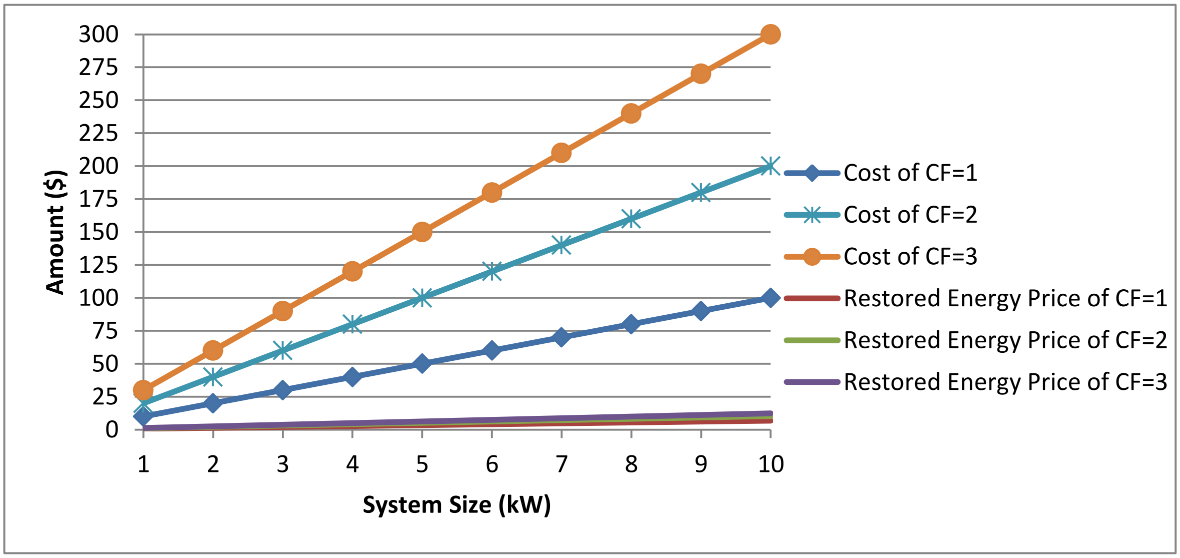


Figure 4.25 The CRP chart of residential PV systems

Though the cleaning cost of the residential PV systems was not justified as shown in the figure above, residential PV systems owners are still expected to do it, because they consider cleaning the PV array as a part of cleaning the house windows and skylights. The Financial Loss (FL) chart, for residential PV systems, was generated and shown in figure 4.26. The FL chart is a good guiding chart for the residential PV owners to realize the real cost of hiring someone to clean their systems, and to distinguish between the costs of the different cleaning frequencies.

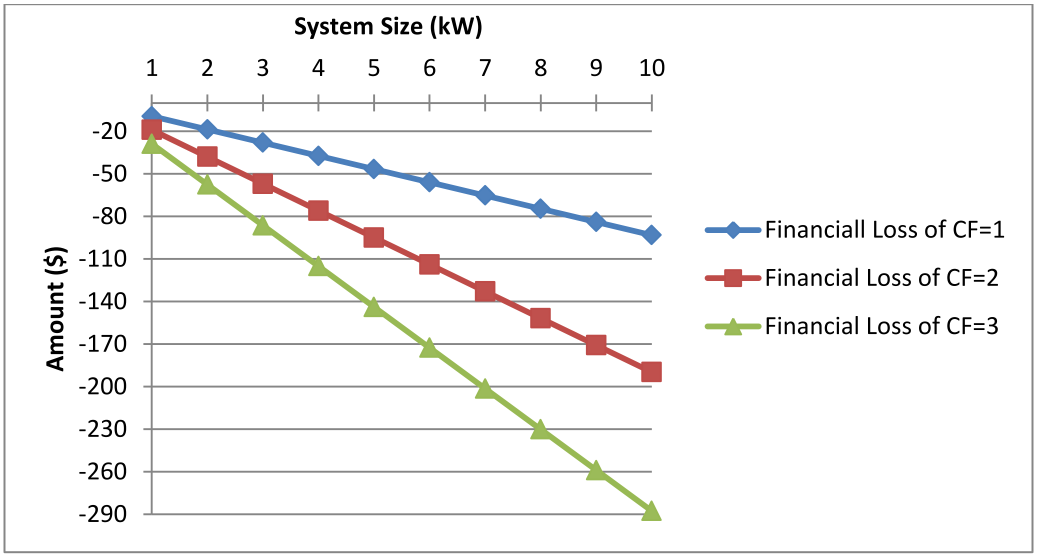


Figure 4.26 The FL chart of residential PV systems

The third chart generated for the residential PV systems was the Cost Justification (CJ) chart (figure 4.27.) Again, this chart is based on a 25-year period of PV operation. This chart is very important to inform the PV system owner about the dollar amount they can invest in mitigating the soiling problem. For the example of 5-kW PV system, less than \$103, \$207, or \$414 would be a good investment if a dust mitigation method was ensured to serve 25 years, lowering the annual soiling loss to -1.4%, -0.96%, or 0%, respectively. In fact, the CJ chart could be of great importance for the developers of dust mitigation means and tools, since the chart can help in realizing the economic benefit of the soiling solution.

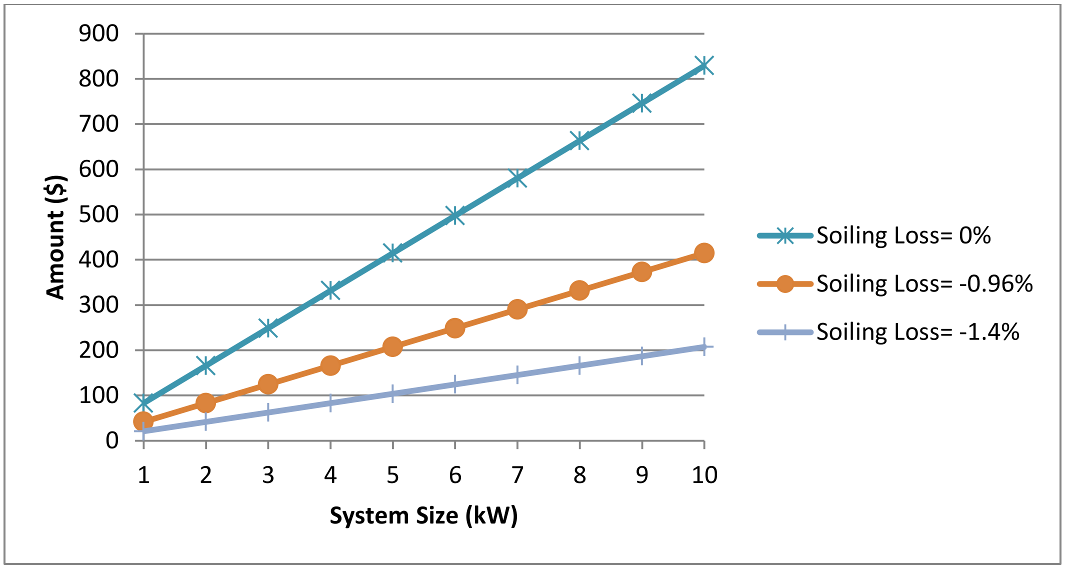


Figure 4.27 The CJ chart of residential PV systems

In this study, commercial PV systems were considered systems with size ranges from 25 to 150 kW systems. For such systems, the cleaning cost was considered as $1/ PV module, the price of the restored energy was based on a $0.095/kWh rate (SWEEP, 2014). Figure 4.28 shows the CRP chart for the commercial PV systems. The starting point for the lines of the restored energy ranges from almost $15 to almost $27, which is considered too low compared to the starting points of the lines of cleaning cost. Therefore, hiring some company to clean the PV arrays of the commercial PV systems cannot be economically justified. The financial loss chart was also generated for the commercial PV systems (figure 4.29), in order to quantify the loss in dollars for those who have no choice but hiring a solar panel cleaning company.

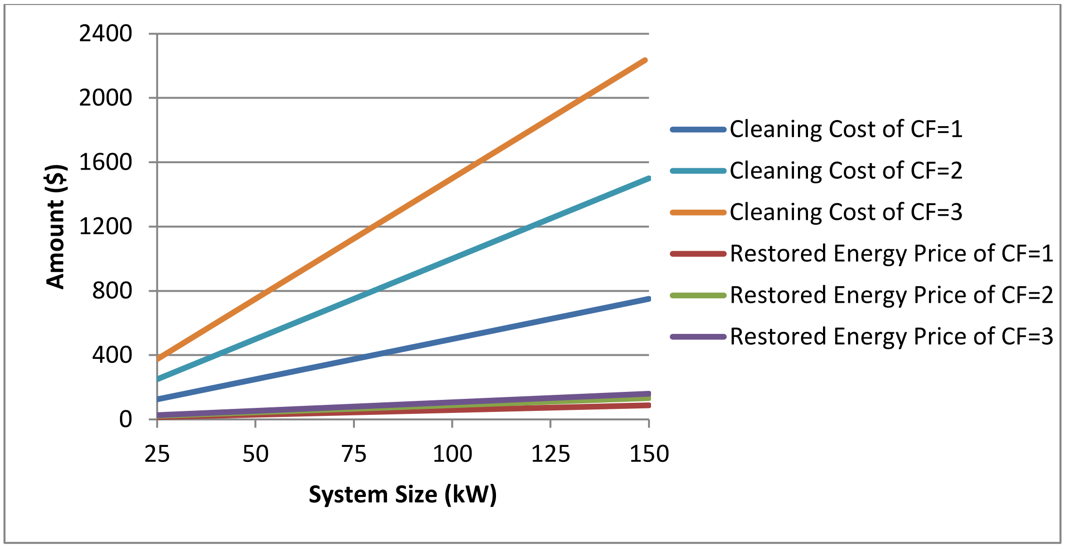


Figure 4.28 The CRP chart of commercial PV systems

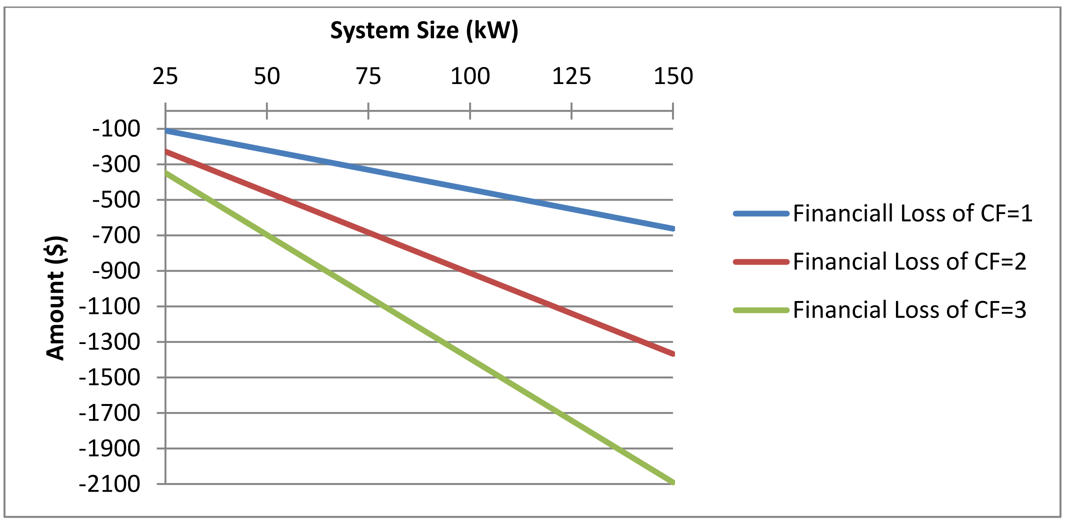


Figure 4.29 The FL chart of commercial PV systems

The Cost Justification (CJ) chart was the third chart generated for the commercial PV systems (figure 4.30.) This chart works as a guideline for those who operate commercial PV systems and would like to invest some amount to mitigate the soiling loss. For the example of 100-kW PV system, less than $1,789, $3,579, or $7,158 would be a good investment if a dust mitigation method was ensured to serve 25 years, lowering the annual soiling loss to -1.4%, -0.96%, or 0%, respectively.

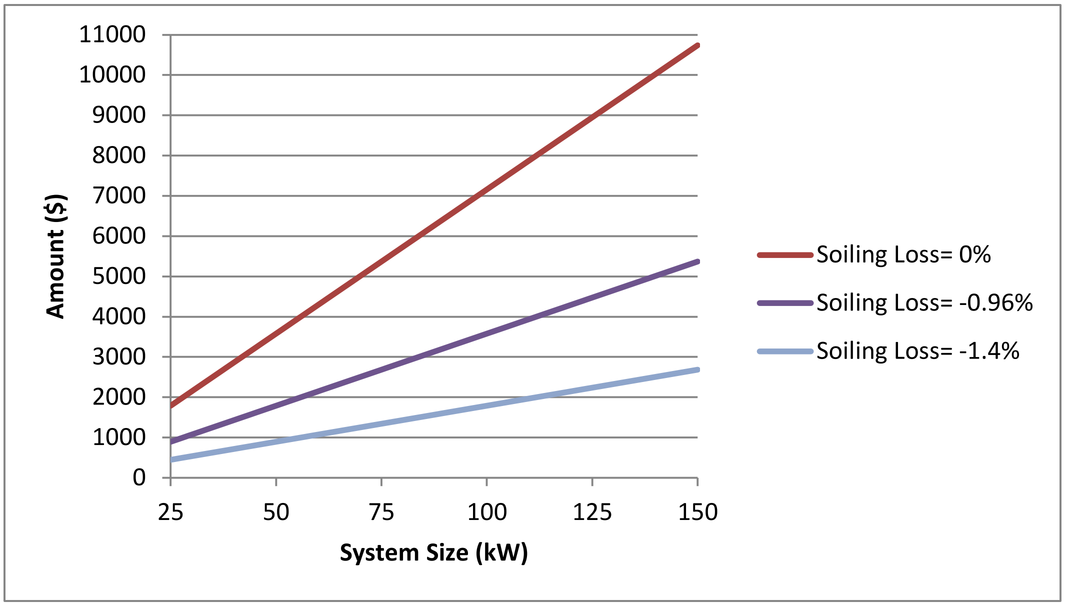


Figure 4.30 The CJ chart of commercial PV systems

The economics of the utility-scale PV systems were also studied. The size of the utility PV applications is commonly 2 MW and more. The module size used in those systems was assumed to be double the module size used in residential and commercial PV applications. Also, the cleaning cost was considered as $0.5/ PV module, the price of the restored energy was based on a $0.13/kWh rate. Figure 4.31 shows the CRP chart for the utility PV systems. From the figure, it can be seen that hiring some company to clean the PV arrays of the utility PV systems cannot be economically justified. The financial loss chart was also generated for the utility PV systems (figure 4.32) in order to quantify the loss in dollars for those who have no choice but hiring a solar panel cleaning company.

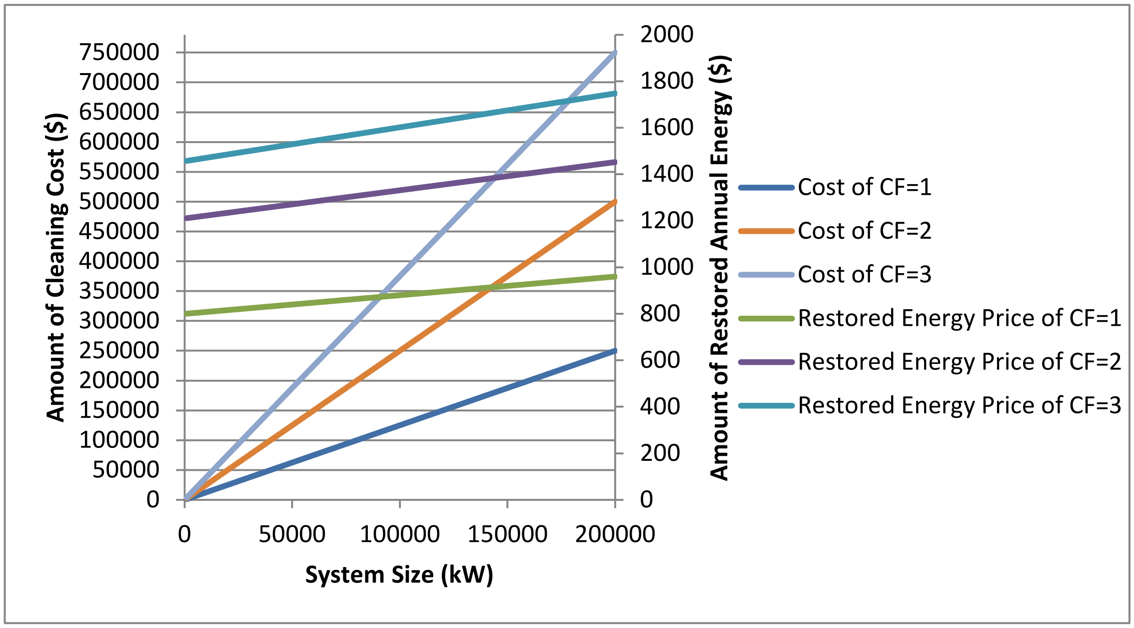


Figure 4.31 The CRP chart of utility PV systems

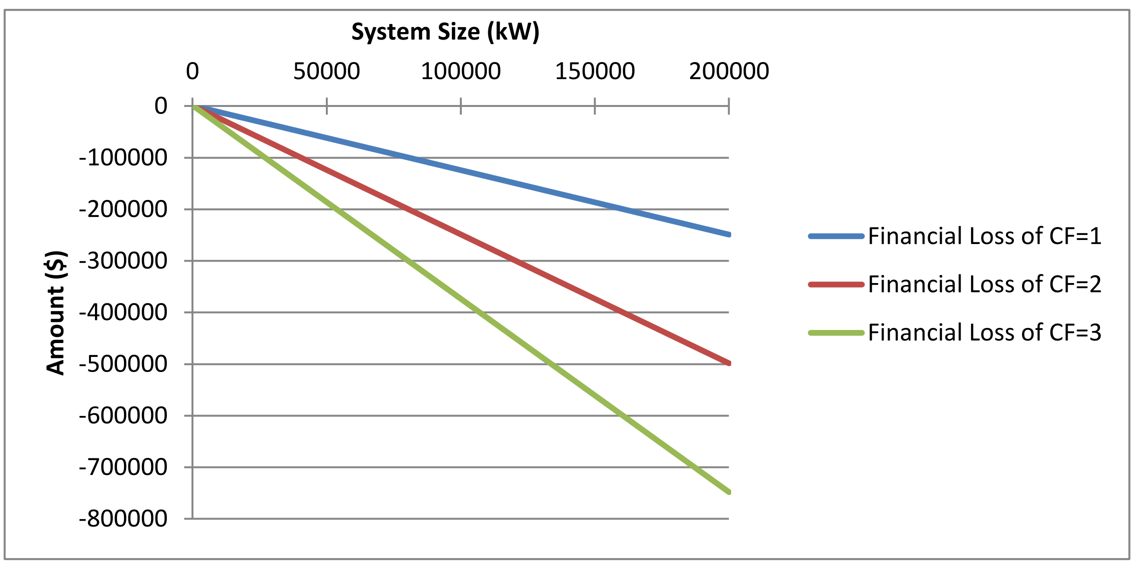


Figure 4.32 The FL chart of utility PV systems

The Cost Justification (CJ) chart was the third chart generated for the utility PV systems (figure 4.33.) This chart works as a guideline for those who operate utility PV systems and would like to invest some amount to control the soiling loss to a specific level. For the example of 5000-kW (or 5 MW) PV system, less than $24,589, $49,178, or $98,356 would be a good investment if a dust mitigation method was ensured to serve 25 years, lowering the annual soiling loss to -1.4%, -0.96%, or 0%, respectively. The CJ chart, for the utility PV applications, is expected to be of more importance since those systems sometimes are built to meet a specific power rating and controlling soiling could be one of the means to do so.

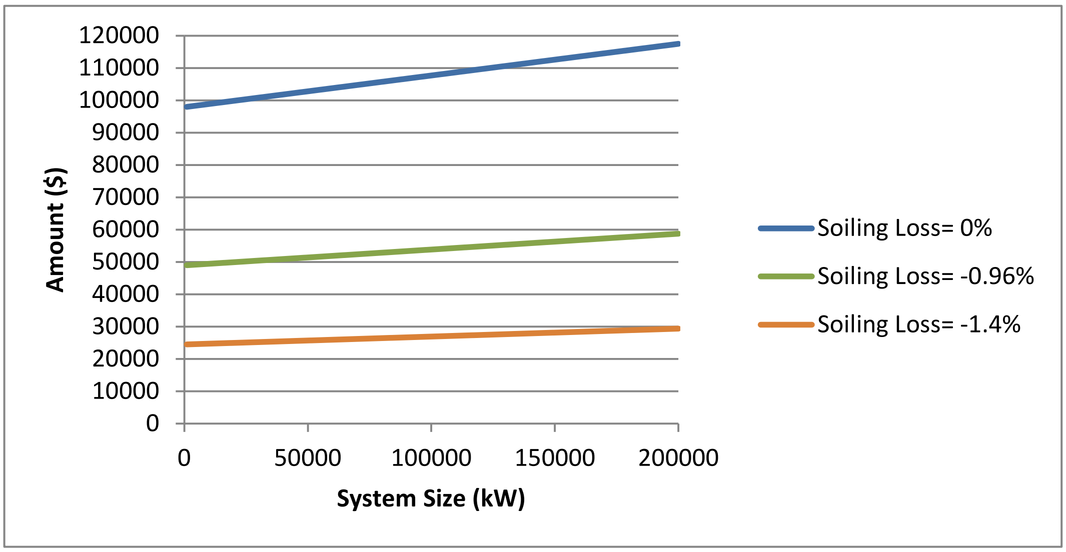


Figure 4.33 The CJ chart of utility PV systems

To recap, soiling loss was monitored and simulated for the past 10 years in Mesa, AZ. After realizing the average soiling pattern, different cleaning frequencies were tested for their effectiveness in mitigating the annual soiling loss. Finally, the financial analysis was done for all different PV applications considering different cleaning frequencies. In the next chapter, the main conclusion and recommendations out of this study will be presented.

5- CONCLUSION AND RECOMMENDATIONS

The soiling loss was monitored and studied for PV modules mounted on a mock rooftop at ASU-PRL testing field with 20° tilt angle. After three months of monitoring (May till July, 2014), daily soiling rate was obtained. To study the financial impacts of soiling on PV modules, cleaning frequency optimization analysis was conducted. Additionally, a detailed study of the climatological relevance to soiling was discussed. The following conclusions were drawn from the results of the study:

1. Soiling loss is not evenly distributed in PV solar arrays; the module location plays a role. For the same exposure time to natural soiling, minimum soiling loss was noticed in the center modules of the mock rooftop system, while higher soiling loss was noticed in those modules close to human activity and sand-covered ground. Though not investigated, wind direction is expected, also, to play a role in causing the soiling non-uniformity among the PV modules.
2. Soiling loss increases as angle of incidence (AOI) increases. At high AOIs, soiling loss increases on higher rates, especially in higher soiling levels.
3. Heavy rainfall of 0.52 in. was enough to fully clean a dirty PV module with -2.3% soiling loss.

4. Light rain worked as a cleaning agent in the case of dirty PV modules, while the (dust carrying) light rain increased the soiling loss in the case of clean PV modules.
5. Being accompanied with light rainfall, dust storms in Arizona do not severely affect the performance of the PV modules (-0.62% was the increase of soiling loss after the dust storm on July 27th).
6. Soiling loss showed no dependence on both air and module temperatures.
7. Relative humidity and wind speed are the main climatological factors relevant to the soiling loss. As relative humidity increases, soiling loss increases. As wind speed increases, soiling loss decreases, provided that the wind is not high enough to lift up/carry dust with it.
8. The cleaning effect of high winds gets even higher when they stay for multiple consecutive days.
9. It was noticed that the highest daily wind speeds occur when the relative humidity is at its lowest. Thus, the cleaning potential due to high wind speeds is higher during such times.
10. During the dry season, the daily soiling rate for 20^{o} tilt was obtained as -0.061%.
11. After simulating the soiling loss for 10 years, the average annual soiling loss was obtained as -1.91% for 20^{o} tilt
12. The average annual soiling loss was found as -1.43% for the wettest year (2004), and -2.24% for the driest year (2007) for 20^{o} tilt
13. Soiling loss has a fixed annual cycle that happens most of the years.

14. For 10 years, there was no significant variation in the average annual soiling loss between one year to another.
15. In case of cleaning the PV modules once a year, June 2nd was found as a recommended day for cleaning. This would lower the annual soiling loss from -1.9% to -1.5%.
16. In case of cleaning the PV modules twice a year, June 2nd and October 23rd were found as recommended days for cleaning. This would lower the annual soiling loss from -1.9% to -1.3%.
17. In case of cleaning the PV modules three times a year, May 21st, June 12th, and October 23rd were found as recommended days for cleaning. This would lower the annual soiling loss from -1.9% to -1.2%.
18. When the soiling is just due to dust, hiring some company to clean the PV modules is not cost effective.

From the results and conclusions found in this study, the following recommendations are suggested for the public:

1. In case the soiling is just due to dust, cleaning the PV modules of typical residential systems with 20^{o} roof pitch is not cost effective and not recommended.
2. If the owner of a PV system decides to clean the PV modules for some reason, following the recommended days of cleaning, mentioned in conclusion, is recommended. Additionally, using the financial charts, presented in chapter 1-4, is recommended as financial guidelines.

3. Solar panel cleaning companies may consider following the cleaning guidelines presented in conclusion.

For improving this study in the future, the following suggestions are presented for future researchers:

1. The setup of the soiling monitoring should be kept running for multiple years to enable obtaining more data to increase the confidence level.
2. Two different daily soiling rates should be obtained for the two soiling seasons of this site (mid-April to mid-July; mid-September to mid-December).
3. The experiment setup should include modules with different tilt angles.
4. The new suggested design for the mock rooftop is shown below:

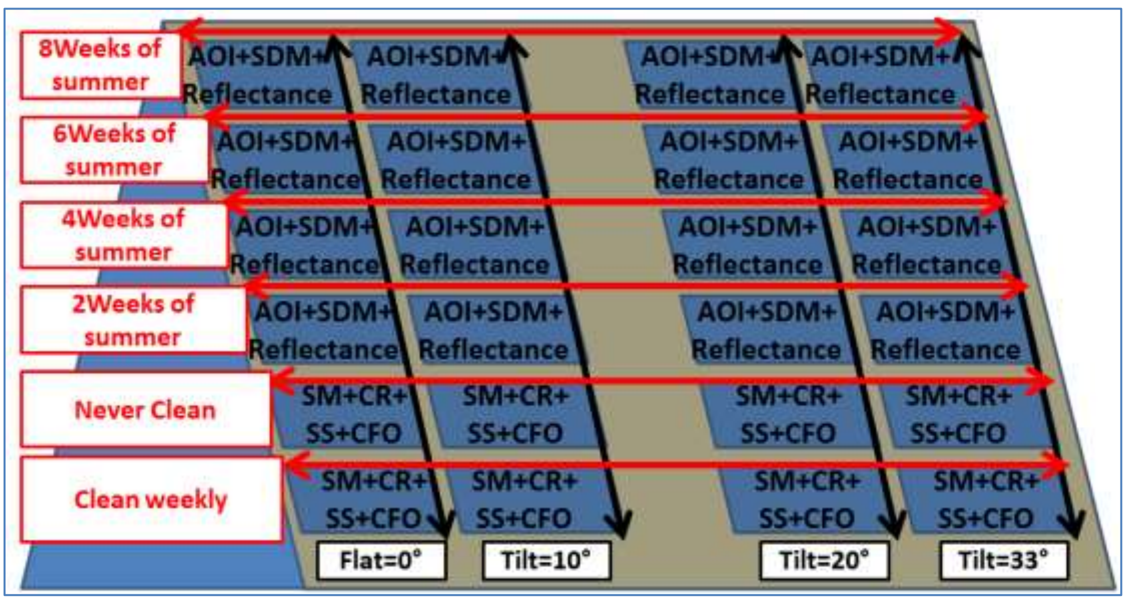


Figure 5.1 The suggested new design for the mock rooftop setup

Where AOI= study the angle of incidence effect on soiling, SDM= Soiling Density Measurement, Reflectance= measuring the reflectance loss due to soiling, SM= Soiling Monitoring, CR= Climatological Relevance analysis, SS= Soiling Simulation, and CFO= Cleaning Frequency Optimization.

As shown above, each column of the mock rooftop should have PV modules with different tilt angle. As they are good representatives of PV installations in AZ, the chosen tilt angles were 0°,10°, 20°, and 33°.
On the other hand, each row of the rooftop should have different cleaning frequency. The bottom row should be cleaned weekly, while the row above it should never be cleaned. The upper four rows should be cleaned within the dry summer season in four different cleaning frequencies: after 2, 4, 6, and 8 weeks from the beginning of the summer season. From the results of this thesis, the summer period usually starts from mid/late April till the beginning/mid of July.

PART 2:
VALIDATION OF SOILING LOSS MODEL USING ACTUAL RESIDENTIAL SYSTEMS

6- INTRODUCTION AND STATEMENT OF THE PROBLEM

Introduction

With the increasing growth of Photovoltaic (PV) installations around the world, a greater emphasis on the performance of those systems is needed to ensure the feasibility of these kinds of investments. It is important to operate the PV modules in such a way they perform at their best conditions. The performance of the PV modules is affected by several factors including irradiance level, temperature, and soiling.

Soiling is a PV performance issue which is caused by dust deposition and accumulation on the top surface of the PV modules. The soiling layer results in reducing the incident light coming into the PV module and, in turn, reducing the power output of the module. Soiling is becoming an important research area in order to deeply understand its impact on PV modules and to develop effective dust mitigation approaches to maintain a favorable performance of PV systems, especially those in the desert regions.

Soiling has a negative impact on the performance of the Photovoltaic (PV) modules. This effect varies from region to region, depending on the climate and environment. In fact, the soiling effect even changes within one region. This varying nature of the soiling loss makes it hard for one to generalize the soiling loss percentage for one region based on a few recordings of the soiling loss. Realizing this fact emphasizes the need of finding out more statistically supported figures for the soiling loss percentages. The percentage of the soiling loss in one region should be obtained from, and validated by, a considerable number of soiling loss measurements in that region.

Need for the Project

Photovoltaic Reliability Laboratory (ASU-PRL) aims to study and measure the soiling loss of PV modules in different locations in the state of Arizona. This would enable obtaining location-specific figures that represent the output loss in PV modules due to soiling. Those figures should have a high level of accuracy, and this fact would make them a valuable contribution to develop the PV performance modeling. Using those figures would result in more accurate modelling of the soiling loss on the PV system performance in different locations and times of the year. Following the first part of this thesis, the results of this second part will be used to validate the daily soiling rate obtained in the first part.

Soiling effect has been quantified by different previous studies, proving that soiling is an obvious issue to consider. However, such studies were not statistically powerful enough since they represented a small number of locations in which the soiling loss was recorded. Any US state has different cities with different climatic and environmental conditions. Recording soiling loss in only one city of a state could lead to misleading figures that are inaccurate for the other cities in that state. Thus, there is a strong need to record the soiling loss as much as possible in different locations and times.

Statement of the Problem

The objective of this study is to find out the monthly and daily soiling rates in different locations throughout the Phoenix area, and then use those soiling rates to validate the soiling rate obtained in the first part of this thesis.

Research Objectives

The main purpose of this project is to come up with location-specific soiling rates throughout the Phoenix area, and validate the soiling rate obtained for the mock rooftop system in the first part of this thesis. Additionally, the data collected from the residential PV systems can help in providing more information that lead to more conclusions. Other expected outcomes of the study include the following:

1) Studying bird dropping effect
2) Studying the water consumption used to clean the PV modules
3) Mapping the soiling loss for the Phoenix area

Limitations of the Project

The soiling test is designed to be as simple as possible for the cleaning companies. This dictates using some easy-to-use, but not very accurate instruments, like clamp-on meter and the infra-red thermometer.

Definition of Terms

The following terms are commonly used in this project:

Soiling: The situation in which PV top surface is partially or fully covered by dust or other pollutants.

Dust: very small particles with diameter less than 500 µm. (Mekhilef et al., 2012).

Dust deposition: "The amount of sediment that impacts on a unit surface in a unit time" (Goudie and Middleton, 2006).

Dust accumulation: "The amount of sediment that remains at a unit surface at the end of a particular time interval" (Goudie and Middleton, 2006).

Angle of Incidence (AOI): "The angle between the sun's rays and a line perpendicular to the array surface" (Dunlop, 2010).

Exposure Time (ET): the duration in which the PV module is exposed to the natural soiling without being cleaned either naturally by rainfalls or manually by washing

Summary

This chapter presented the idea of the soiling evaluation study which is being conducted by the ASU-PRL. The study aims to collect soiling data from PV systems installed in the Phoenix area, exploring the diverse soiling effect throughout different locations and during different times of the year. The outcomes of this study are of great importance for the developers of the PV performance models. Additionally, the results of this study were used to validate the results of the first part of this thesis.

7- REVIEW OF RELATED LITERATURE

Introduction

While operating in the field, the performance of PV modules is affected by the operating conditions such as irradiance and temperature. Low irradiance and high temperature negatively impact the performance of PV modules. Soiling, or dust accumulation on the surface of PV modules, is also considered one of those operating conditions which negatively affect the performance.

Globally, the negative effect of soiling on solar arrays varies from region to region. In many regions, the soiling effect could be considered low, especially for small-scale PV systems. However, in some regions in the world, especially the solar-rich regions, like the Middle East, North Africa, India, and China, soiling impact could be very serious on the feasibility of the solar power investments. This is the reason behind the fact that the research on soiling has been there for several decades until today, and it is getting more attention as those countries are moving to adopt solar power technologies. The current research status does not indicate a full understanding of the soiling mechanisms and its impact on solar arrays. Additionally, and more importantly, there is a strong need to develop more efficient ways to mitigate the soiling problem.

Evaluating the potential for solar power in the given location is not limited on estimating how much solar radiation is received. Other environmental conditions factor in the expected performance of the PV systems. Soiling is one of those conditions which can cause considerable power reduction in the output of the PV modules.

Research on soiling effect on solar collectors is a multidimensional research area that includes many topics including electrical engineering, climatology, physics, chemistry, and material science. A clear understanding of the operation and properties of solar modules is needed. On the other hand, soiling problem is location-specific so it is important to study the climatological details of the location where the solar system is planned to be installed. That helps in determining the influence of the climatic parameters like wind, rain, and humidity. The location dependence is also related to the surrounding environment and activities which also play a role in the nature and rate of soiling.

Soiling Effect in Theory

Soiling effect is an obvious effect that can be seen in the field measurements and readings. The logic behind it is quite straight forward: dust obstructs sunlight from being transmitted to the PV module, which in turn reduces the amount of solar energy converted to electricity. However, it would be more convincing if we can theoretically realize the soiling effect. This can be easily done by looking at the following equation:

$$(\tau\alpha)G_t = \eta_e G_t + U_L(T_C - T_a)$$

where G_t is the solar radiation, η_e is the module efficiency, U_L is heat loss coefficient, $(T_C - T_a)$ is cell-to-ambient temperature difference, and $\tau\alpha$ is transmittance-absorptance product. The left hand side of the equation represents the input energy to the PV module while the right hand side represents the output. As can be seen, transmittance, which basically represents the cleanness of the top of the PV module, has a direct impact on the energy input to the PV module. When $\tau\alpha$ is equal to 1, that means the module surface is all-clean. As $\tau\alpha$ gets smaller, it means the surface suffers a soiling problem (figure 7.1). Thus, the energy received from the sun to the module surface is dictated by how much the fraction of the $\tau\alpha$ is, which is basically dictated by the cleanness of the top surface (Kalogirou, Agathokleous, and Panayiotou, 2013).

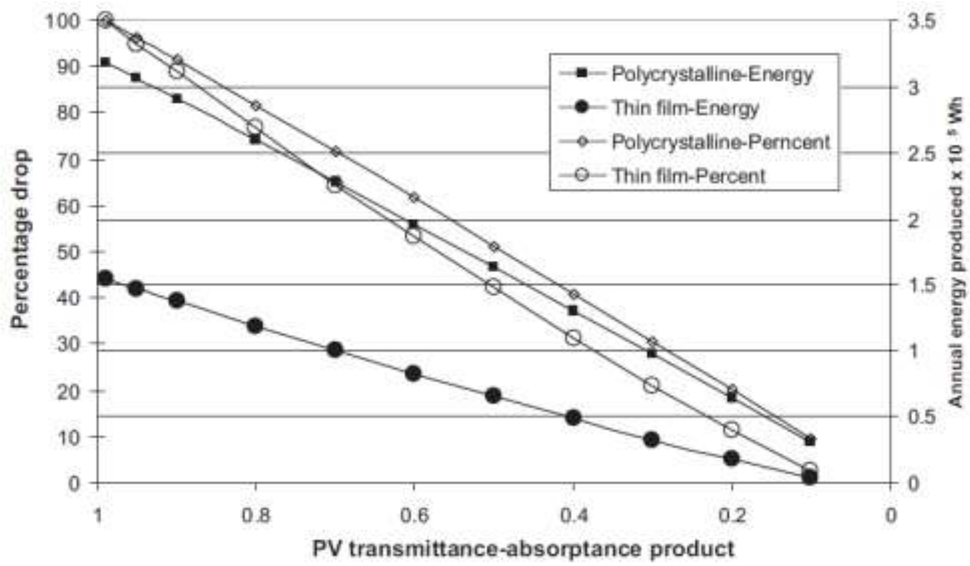


Figure 7.1 Soiling effect on the transmittance of the PV module

Soiling Effect in Numbers

Many studies in different regions and countries have been conducted to quantify the performance loss in PV modules due to soiling. The United States has a relatively low average in the power drop due to soiling, which is 1 – 4.7% reduction. Hammond et al. (in AZ) reported 2.3%, 4.7%, 8% reduction with angle of incidence (AOI) of 90°, 24°, and 58°, respectively. Countries in Middle East and India suffer more because of their geographic locations and weather dynamics. In Saudi Arabia, for example, the soiling loss could reach 60% after the incidence of dust storms (Sarver, Al-Qaraghuli, and Kazmerski, 2013).

It is worth mentioning that a lot of previous soiling studies significantly lacked a systematic way of expressing the soiling loss. They also lacked some specifics like mentioning the density of the soiling layer, the percentage of the reflected light due to soiling, the AOI dependence, and the environment and surrounding of the test modules.

The Variability of Soiling Loss over Different PV Installations

Soiling loss of PV modules is location specific. The rate of soiling varies from one location to another, depending on different factors like climate, the nature of the location such as a rural or an urban area, and the surrounding activities such as bad traffic, agricultural, or industrial. In their study in California, Caron and Littmann proved the nature of variability of soiling by comparing the monthly soiling rates of low desert and dry agricultural regions. Compared to 11.5% monthly rate of soiling loss in the heavy agricultural regions, less than 1% was found in the desert area (Caron, and Littmann, 2013). Soiling varies even over short distances, as demonstrated in a study in Italy where the performance reduction for one power plant after 8 weeks of soiling is 6.9%, and in the other nearby plant is 1.1% (Paven et al, 2011).

Other specifics of the PV systems also play a role such as the mounting system, the height of the mounting, and the array orientation. Since they are distributed differently, living beings like trees and birds could also add to the soiling loss differently in different locations.

Investigating the soiling effect in a relatively large number of PV installations distributed in a region is very important and helpful in obtaining a reasonably accurate number that represents the soiling loss in that region. Two previous soiling studies were based on a large number of samples of PV systems. The first one dealt with 250 sites in California and Southwestern United States. After controlling the quality of the data, the study is left with 46 sites. The soiling loss was considered to be due to performance reduction over time after correcting for the module temperature. From this study, it is found that the average daily soiling loss in dry periods is 0.2% (Kimber et al., 2006).

The second study was conducted on 186 residential and commercial PV systems in different parts in California. The soiling loss was obtained by finding the efficiency reduction with comparing the daily energy production of the PV system with the solar source data from the SolarAnywhere (SAW) database. The study showed the variability in the soiling loss between and within the regions of the PV installations. Out of this study, it is found the average daily soiling loss in dry periods is 0.051% over the 186 sites (Mejia, and Kleissl, 2013).

Available Solutions for the Soiling Problem

The first step to mitigate the soiling on the solar collectors is to understand the problem, being aware of the climatological influence where the PV systems are installed. The main categories for the mitigation approaches are restoration and prevention. Restoration is when some method is used to remove the soiling layer from the surface of the solar modules. On the other hand, prevention involves methods used to avoid the soiling from happening or further accumulating. Restoration of the PV output lost due to soiling can happen by the natural rainfalls, washing, or using some mechanical methods like wiping the surface with a piece of cloth, using air nozzles (with/without water), and automated cleaning systems. On the other hand, preventive methods include stowing, facing down, the PV modules during dusty weather, Electrostatic Discharge Screens (EDS), and anti-soiling coatings (Sarver, Al-Qaraghuli, and Kazmerski, 2013).

Before using any of the above-mentioned approaches, the feasibility of using any approach should be justified. If one needs to justify the use of one mitigation approach against not using it, detailed cost-benefit analysis must be done, comparing the cost of that mitigation solution and the potential cost resulting from the performance loss. Sometimes, mitigation solutions are needed for sure, but the best one is not realized. In that case, comparison between the different solutions must be done in terms of their efficiency, cost, and water consumption (Sarver, Al-Qaraghuli, and Kazmerski, 2013).

The most basic solution to mitigate soiling is obviously to wash off the soiled surfaces of the PV modules. Washing offers a restoration of most of the power lost in many cases. It is also considered an easy approach. However, washing requires paying attention to some guidelines in order to have a professional practice and satisfactory results. This includes recommendations like using demineralized water and chemical agents to save the water consumption and ensure smooth washing. Washing in the early morning, when the dew is there on the surface, is a good time for washing, ensuring smooth washing and, in turn, not damaging the surface being washed (Sarver, Al-Qaraghuli, and Kazmerski, 2013).

Summary

Soiling effect has been quantified by different previous studies, proving that soiling is an obvious issue to consider. The accumulated dust on the top surface of the PV module obscures the incoming sunlight onto the PV module, which in turn affects the module performance. Soiling loss varies from one location to another, depending on the environment, climate, and other system specifics. Thus, obtaining the soiling loss for a region should come from studying a reasonable number of PV sites in that region. This chapter also presented some of the available solutions to either prevent, or mitigate the soiling loss. Preventive methods include anti-soiling coatings, and electrostatic discharge screens. Restorative methods include washing, mechanical cleaning, and automated cleaning equipment.

8- METHODOLOGY

Introduction

The main goal of this project is to collect soiling data from as many PV systems as possible throughout the Phoenix area in Arizona. To be able to do this, ASU-PRL started collaborating with solar panel cleaning companies that serve in the Phoenix area. Those companies are exposed to many different PV installations in different cities like Phoenix, Mesa, Chandler, Tempe, etc. By working with such companies, collecting soiling data for different locations is easily achievable.

Data Collection

A soiling checklist sheet has been developed by ASU-PRL in order to be used for a comprehensive soiling evaluation. ASU-PRL provided those companies with that sheet and the equipment needed to take readings required for the soiling evaluation. After having collected a lot of data, the data was processed and analyzed to get the desired results and outcomes.

The soiling checklist sheet helps to record data that gives a detailed image on the PV modules being observed (see appendix C). Basic data from that sheet includes general information on the PV system and the location of the installation, readings of string operating current before and after cleaning, and soiling-related visual inspection data. Pictures and dust samples are also included within the collected data.

The cleaning companies were provided with a Soiling Testing Toolkit (STT), which includes all the instruments needed for the measurements in the soiling checklist sheet. Each company got a guiding flyer that shows how to use each instrument of the Soiling Testing Toolkit (see appendix D). The instructions of using those instruments were provided from the manufacturers' manuals besides some additional points from the researcher.

Soiling Checklist Sheet (SCS)

The main purpose of the Soiling Checklist Sheet (SCS) is to make the data collection easier for the cleaning company worker who performs the data collection. Also, it is a systematic way that ensures that all the details needed for the data processing and analysis is recorded for the researcher. Since its very first version, the SCS has gone through a lot of editions till it reached the final compact version that fits the needs of both the researcher and the cleaning companies.

The soiling checklist sheet has five sections: general information, PV system information, before cleaning, dust sampling, and after cleaning. The general information section includes data like date and time in which the cleaning is taking place. Since the soiling is affected by the surroundings of the PV installation, the first section includes the address of the location and its nature whether it is in or around a city, rural, industrial, agricultural, or desert area.

The second section of the SCS gives information about the PV system like the system size and type. The mounting system used in the observed PV system can have an obvious impact on the soiling formation. That is why this section includes some details on the mounting systems used in the PV installation. Measuring the dimensions of the installed PV modules is also required since they are used in water consumption analysis of this study.

The third section covers the same readings before cleaning the PV array. Those readings are necessary to enable the researcher to evaluate the performance of the observed PV modules before getting cleaned. In the same section, some visual inspection for the dirty modules is done including taking pictures.

Dust sampling is necessary for finding the soiling density later. The fourth section only addresses the dust sampling. Washable mini lint rollers are used for the dust sampling; more details on that will follow later in this chapter.

Finally, the fifth section is designed to help with collecting data that is necessary for the performance evaluation of the PV modules after getting cleaned. Using data from sections 3 and 5, the percentage of the performance restoration, or the performance reduction due to soiling, can be calculated. Section 5 covers other information like the water consumption, cost of the cleaning, and the cleaning duration.

Soiling Testing Toolkit (STT)

To fully fill the SCS, different readings need to be taken from the PV site. A Soiling Testing Toolkit (STT) contains different instruments and tools that help with filling the SCS. The instruments are a measuring tape, inclinometer, irradiance meter, clamp-on meter, infrared (IR) thermometer, and dust sampling tools. The measuring tape is used for measuring the dimensions of the PV modules. On the other hand, the inclinometer is used to measure the tilt angle of the fixed-tilted PV arrays.

In the data processing, the irradiance, the generated module current, and the module temperature (before and after cleaning) are needed. Those measurements are taken by the solar irradiance meter, clamp-on meter, and IR thermometer, respectively. All of those instruments are easy to use and do not require the cleaning company worker to disconnect or connect any wires.

Because of its convenient use, Daystar solar meter had been used as the irradiance sensor. After analyzing a couple of systems, it was noticed that the readings of the Daystar meter are inconsistent, especially when the testing was performed at low irradiance (off the solar window.) To investigate more, an experiment was performed at the ASU-PRL testing field, testing the consistency of the Daystar solar meter with the solar reference cell used in the lab. Also, MSX01 mini solar panels were tested to see if they could be good alternatives for the Daystar solar meters. The setup of the experiment is shown in figure 8.1. Readings of all the instruments (reference cell, Daystar meter, and MSX01) were recorded from 8:30 am to 4:30 pm. As shown in figure 8.2, the Daystar irradiance readings were not consistent with the readings of the reference cell, while the readings of the MSX01 mini panel were consistent. The reason behind that inconsistency of the Daystar solar meter was the fact that it has a plastic superstrate on the top of the built-in solar cell of the meter, which is not the case in the reference cell and the MSX01 solar panels in which the superstarte is made of glass. Different superstrates have different transmission responses with different angles of incidence (AOI), especially in high values of AOIs in the early morning and late afternoon. Out of this experiment, the decision of using MSX01 solar mini panels instead of the Daystar solar meters in reading the solar irradiance was made.

To use the MSX01 as a solar irradiance sensor, a digital multi-meter with a 1Ω resistor were connected across the MSX01. After obtaining the calibration factors of the tested MSX01s, the voltage across the resistor was taken as the representative value of the solar irradiance. Four different MSX01s were tested. The calibration factor for 3 of them was 190 mV while one of them had a calibration factor of 195 mV.

Figure 8.1 The setup of testing different solar irradiance sensors

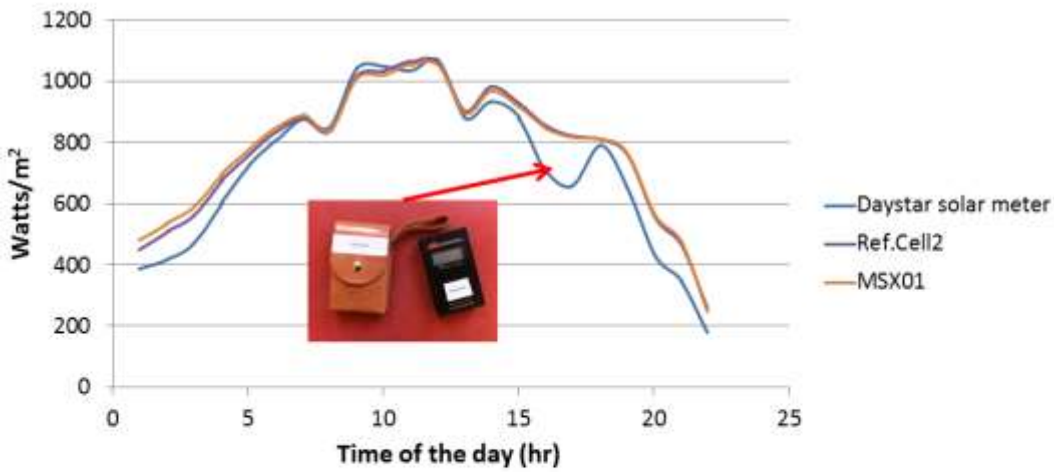


Figure 8.2 Solar irradiance readings from 8:30am to 4:30pm

Dust Sampling Tools

In any soiling study, measuring the density of the soiling layer is important since it gives a good sense of how dirty the PV module is. Realizing the importance of having a fairly accurate measurement of the soiling density, the researcher has experimented with different tools. It started with using a sampling method based on the suction of the dust from the surface of the PV module by a vacuum cleaner. Unfortunately, that method was not accurate enough. The same inaccurate results were found using cotton pads and tissues.

Using paper-based lint rollers in dust sampling showed promising results. However, those kinds of lint rollers were combined with some technical difficulties. Eventually, after a series of experiments, mini washable lint rollers (shown in figure 8.3) were found as the most accurate and practical method of dust sampling. Later, a standard operating procedure was developed for dust sampling using the washable lint rollers to ensure the consistency of the soiling density measurements (see appendix E).

Figure 8.3 Mini washable lint rollers used for dust sampling

Data Processing and Analysis

After collecting the soiling data from the PV systems, the cleaning companies returned the SCSs filled with the dust samples. The next step was to start processing and analyzing the data. An Excel worksheet was developed to process the collected data. All the data from the SCSs were copied to the Excel sheet, and then used to calculate some figures like the monthly soiling loss for the PV system, water consumption, cleaning duration and cost per module.

The soiling loss was calculated by two different methods: the loss of the operating current before and after the cleaning, and the loss of the power before and after cleaning. The former was done using the readings of the clamp-on meter directly from the wire coming out of the module, while the latter was done using the inverter readings. It is important to mention that the results are based on the first method of the current readings, except some cases where the second method appeared to be more accurate than the first one. Sometimes, the results of the second method were used to verify the results of the first method.

To have a base of comparison, the monthly soiling loss was calculated. It was calculated as the soiling loss after the dry period divided by 30 days. Dry period means the period in which no natural or manual cleaning for the PV module happened. The rainfall data, which represents the natural cleaning data, was taken from The Arizona Metrological Network (AZMET) by the University of Arizona. The manual cleaning data was obviously taken from the records of the cleaning companies.

Soiling losse varies thorough the day, i.e. soiling effect varies with respect to the variations of the Angle Of Incidence (AOI). Since the cleaning times were different from one PV system to another, AOI correction has been done for all the soiling losses obtained from the different PV systems. The method used for the AOI correction was discussed in chapter 1.3.

Summary

To study the soiling loss in different locations of the Phoenix Area, ASU-PRL has collaborated with solar panel cleaning companies to collect the data from real PV systems before and after cleaning the PV modules. The cleaning companies were provided with a checklist to fill out, and with the needed equipment to take the readings before and after the cleaning. After submitting them to the ASU-PRL, the data were processed and analyzed to achieve the research objectives.

9- RESULTS AND DISCUSSION

Introduction

Soiling-related data of six PV residential systems have been measured, collected, and processed. All the data was collected during the period of April-June, 2014, and during times close to noon time. All the PV systems, which have been tested, were located within the Metropolitan Phoenix area. However, those PV systems had different settings, designs, and types of surroundings. In this chapter, the results of analyzing the soiling data for the PV systems are presented, along with soiling-related mapping for the Phoenix area.

Soiling Loss in Gilbert, AZ

A small PV residential system, with a total of 12 PV modules, was evaluated. The array was mounted on a one-story rooftop with a tilt angle of 18°. The system was located at the zip code of 85296. The location was characterized as a regular city area. From the records of the cleaning company, the cleaning frequency of the PV system is twice a year. The cleaning day was the 5th of May, 2104, and it happened at 9:00 AM.

Before and after cleaning, basic data was collected like the irradiance, operating current, generated power from the inverter, and module temperature. Bird droppings were found very low. Ten gallons of water were consumed for the cleaning job in about 15 minutes. The water consumption was calculated as 1.98 liter/m^2.

After processing the data, the soiling loss was found as -12.9% after almost 129 days of leaving the PV modules uncleaned. No rain occurred between the last and the current cleaning jobs; that was why the soiling level has reached a fairly high value. After correcting for the AOI, the monthly soiling loss was calculated as -1.90%.

Soiling Loss in Chandler, AZ

Soiling data for two different locations in Chandler were collected. The first site was a one-story house with a zip code of 85248. The number of modules was 28, mounted on a relatively low tilt angle of 13°. The modules were cleaned on the 24th of April, 2014, almost one year from the last manual cleaning job (figure 9.1). However, the modules must have been cleaned by the rainfall (of 0.7 in) that occurred on the 23rd of November, 2013, according to the rainfall data from AZMET. Before the cleaning, low bird droppings were found on the surface of the modules.

Figure 9.1 Side by side image for the PV modules located in Chandler, AZ

After processing the data of the first site in Chandler, the soiling loss was found -12.4% after 152 days of exposure, and the monthly soiling loss was obtained as -2.55%. The water consumption was 30 gallons per the whole system and 2.5 liter per m^2. Almost 30 minutes were taken for the cleaning job. In other words, the cleaning took almost one minute per module.

The second system in Chandler was the biggest system in the whole study with 48 PV modules, mounted on both southern and eastern rooftops of a one-story home with a tilt angle of 22°. The zip code of the location was 85225. The cleaning job for the system was performed on the 12th of June, 2014, almost one year from the last date of manual cleaning. Between the two cleaning jobs, the modules must have been naturally cleaned with the rainfall (0.78 in) that occurred on the first of March, 2013. After 104 days of exposure from the occurrence of that rainfall, the soiling loss reached 14.1%, resulting in monthly soiling loss of -6.08%. Three dust samples were taken from the site. The soiling density for one of the modules was calculated and obtained as 647 mg/m^2. One of the possible reasons for that high soiling density is the fact that the PV array lacks any kind of surroundings that would have been working as dust barriers (see figure 9.2). From the data of the two systems mentioned above, the soiling loss map for Chandler, AZ, was generated as shown in figure 9.3. Taking the average of the two systems, the average monthly soiling loss for Chandler, AZ was obtained as -4.32%, considering 50% of the data was affected by high bird droppings.

Figure 9.2 The second evaluated system in Chandler, AZ

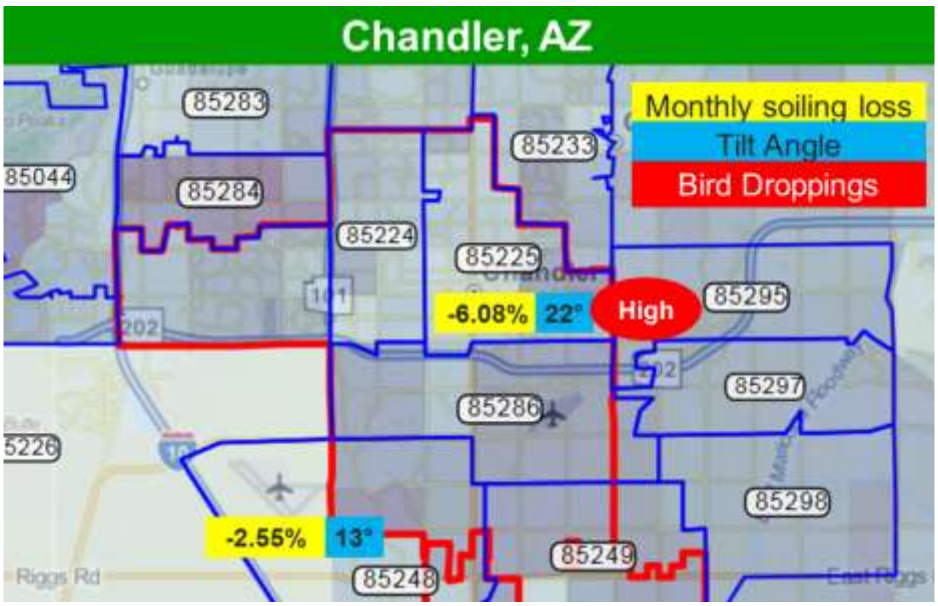


Figure 9.3 Soiling loss map for Chandler, AZ

Soiling Loss in Mesa, AZ

One PV system was studied in Mesa, AZ. The system was located within a zip code of 85209. The system has a PV array of 32 modules, mounted on a two-story rooftop and tilted 17° from the horizontal plane. As shown in figure 2.4.4, the modules were heavily soiled with bird droppings, resulting in very high soiling loss. Surprisingly enough, after cleaning the PV array on the 21^{st} of May (2014), the soiling loss for the module, shown in figure 9.4, was found -81.4%, after almost one year from the last cleaning job, which was on the 1^{st} of June (2013). Considering the rainfall (0.9 in) that occurred on the 1^{st} of March (2014), the monthly soiling loss was obtained as -39.68%, reaching the maximum figure that was obtained among all other PV systems.

Figure 9.4 Heavy bird droppings found in Mesa, AZ (Tilted 17°, Exposure Time (ET) =82 days)

The soiling density was found almost 623 mg/m^2. Comparing the soiling density with other soiling densities of other PV systems, the figure falls within the average values. However, the soiling loss was way far from the soiling losses of the other systems, showing how badly the bird droppings could negatively affect the performance of PV modules. In fact, the soiling loss of 81.4% could have been fairly estimated just by looking at the amount of the bird droppings that covered up the cell located at the lower right corner of figure 9.4. Since they are much more opaque than the regular dirt, bird droppings cause much more light reflection from the surface of the PV module.

Heavy bird droppings are even harder than the regular dirt in terms of cleaning. Therefore, the above-mentioned PV system consumed high amount of water to be cleaned, reaching 30 gallons of water, or 2.4 liter per m^2. Moreover, cleaning the system took more than average time duration, 45 minutes, or 1.4 minute per module.

Soiling Loss in Phoenix, AZ

A residential PV system, with 40 modules, was evaluated in Phoenix, AZ. The modules were mounted on a one-story rooftop with a tilt angle of 28°. The zip code of the PV site was 85032. The location was characterized as a bad traffic area.

The cleaning frequency which the cleaning company contracted with the system owner was 3 times a year. The data from the cleaning job was on the 5th of April, 2014. The soiling loss was found as -7.9%. Given that it rained (0.83 in) on March 1st, 2014, the monthly soiling loss was calculated and obtained as -1.7%. Again, the high cleaning frequency and the high tilt angle are expected to be the reasons behind the relatively low soiling loss. Having no bird droppings on the PV site is another obvious reason for having a low soiling loss.

Soiling Loss in Goodyear, AZ

Being surrounded by desert area, Goodyear was a special place to evaluate the soiling. A PV system of 34 PV modules was evaluated within the zip code of 85338. The modules were mounted on a one-story rooftop with a tilt angle of 20°. The system is usually cleaned three times a year. The cleaning job was done on the 15th of May (2014), while the former cleaning had been done on the 10th of January, 2014. With low bird droppings, the soiling loss was found to be 3.2%. Considering the occurrence of the rainfall (0.74 in) on the 1st of March (2014), the monthly soiling loss, that represents the PV system, was obtained as -1.78%. The soiling pattern and level for the PV modules located in Goodyear, AZ is shown below in the figure 9.5.

Figure 9.5 Soiling in Goodyear, AZ (Tilted 22°, ET=76 days)

Soiling Loss Mapping for Phoenix Area, AZ

The soiling data for six PV systems, located in different cities in the Phoenix area, have been collected, processed, and analyzed. Table 9.1 summarizes the main data and findings for the six evaluated PV systems. For clarifying the abbreviations used in the table, SN stands for system number, ET for exposure time (in days), BD for bird droppings, and MSR for monthly soiling rate.

Table 9.1

Soiling data for the six evaluated PV systems

SN	location	ET	Area type	Height	Tilt angle	BD	MSR
1	Phoenix	36	Bad traffic	1-story	28	No	-1.71%
2	Chandler	152	city	1-story	13	Low	-2.55%
3	Gilbert	129	city	1-story	18	Low	-1.90%
4	Goodyear	76	desert	1-story	22	Low	-1.78%
5	Mesa	82	city	2-story	17	High	-39.68%
6	Chandler	104	city	1-story	22	High	-6.08%

The main goal behind studying all of those systems was to generate an easy-to-read map in which different soiling losses are shown for each city in the Phoenix area. The generated map is shown in figure 9.6. The soiling loss was represented as an average monthly soiling loss, to serve as a comparable soiling loss indicator. Besides the monthly soiling loss, a special (red-colored) legend was shown to indicate how much the soiling loss percentage was influenced by systems that had a high amount of bird droppings. For example, in the case of Chandler, 50% of the systems, upon which the soiling loss percentage was based, had high bird droppings. On the other hand, the soiling losses for cities like Gilbert and Phoenix were not based on PV systems that had high bird droppings.

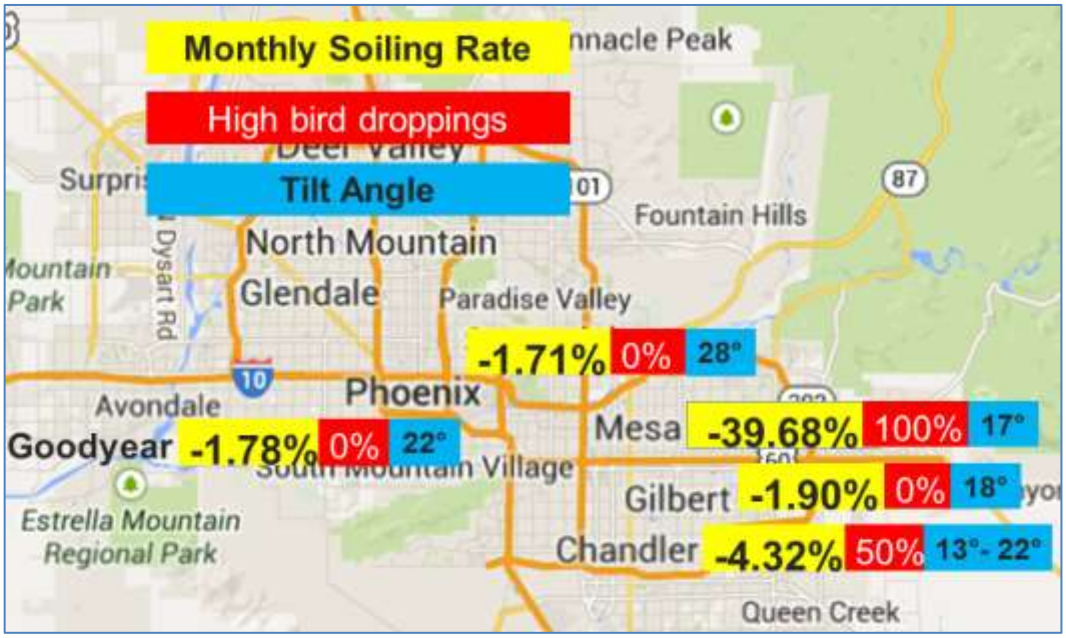


Figure 9.6 Monthly soiling loss map of Phoenix area

The above figure should be of importance for the PV systems designers, installers, owners, and operators, as the map helps give a sense of how negatively the soiling will affect the performance of the PV systems in different cities of the Phoenix Area. The map can also be used for finding the possibility for locations where PV installations will have higher bird droppings. As may be noticed from the map, the level of the bird droppings highly affect the percentages of the monthly soiling losses.

Another map was generated, shown in figure 9.7, factoring out the PV systems that have bird droppings. This kind of map shows the effect of only the soiling due to dirt and other air pollutants. In other words, this map shows the variability of the aerosols deposition from one region to another.

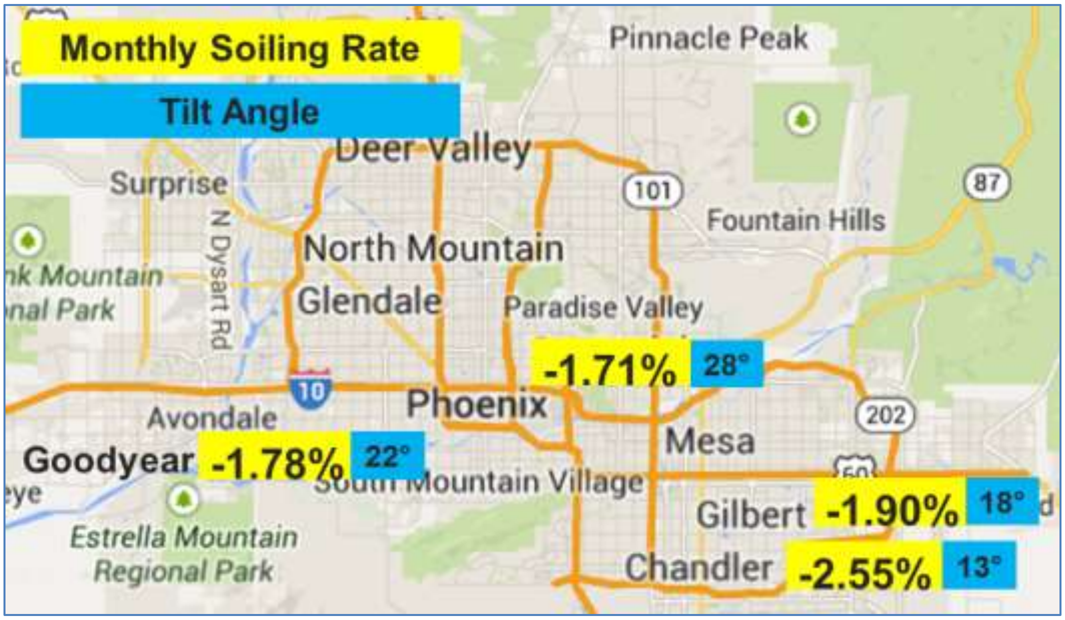


Figure 9.7 Monthly soiling loss map of Phoenix area (heavy bird dropping excluded)

As seen in the above figure, the East valley of the Phoenix Metropolitan area seems to have higher soiling loss rates than the Central and West valleys. The average monthly soiling loss for the East valley was obtained as -2.23%, compared to -1.71% for the Central valley and -1.78% for the West valley. On the other hand, the average monthly soiling loss for the whole Phoenix Area was found as 1.99%. This number could be the only number the PV performance models use from this study, as it is a good representation for the soiling loss in the Phoenix Area, AZ.

Dividing the monthly soiling rates, in figure 9.7, by 30 gives the daily soiling rates, as shown in figure 9.8. As can be seen, the daily soiling rate in the Phoenix area ranges between -0.057% to -0.085% for 13° to 28° range of tilt angle. The average daily soiling rate was obtained as -0.066%. The daily soiling rate found in the first part of this thesis was -0.061%, which falls within the range of the soiling rates found in the second part of this thesis. Thus, the second part of the thesis can be considered as a validation for the first part.

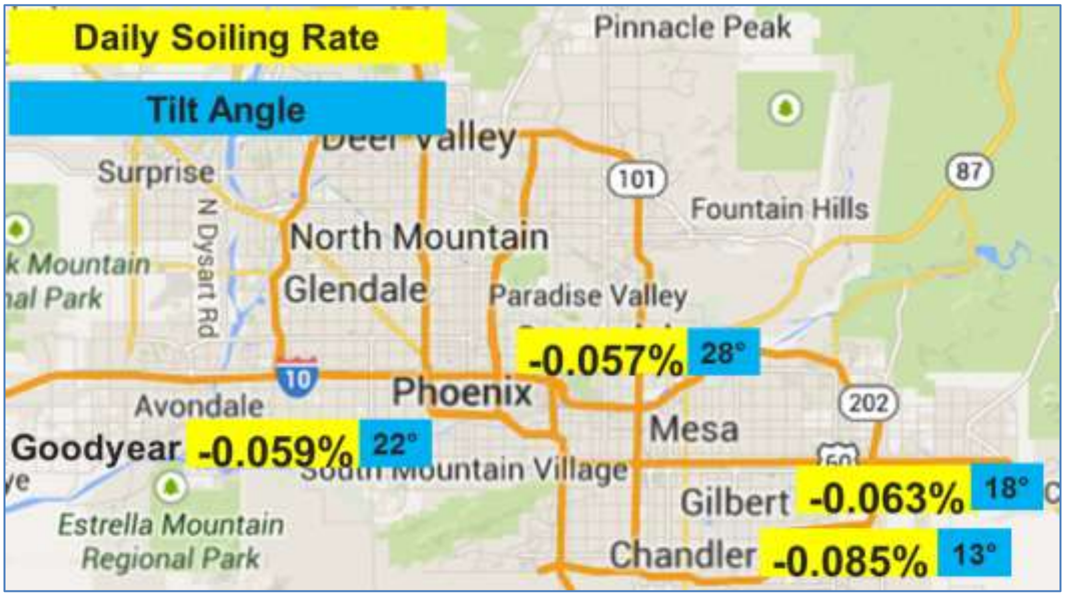


Figure 9.8 Daily soiling loss map of Phoenix area (heavy bird dropping excluded)

It is also noteworthy that the range of the daily soiling rates is close to that range revealed by McCarthy Company for the Metro Phoenix area. While the range found in this thesis was -0.057% to -0.085%, McCarthy Company reported -0.04% to -0.07% (Canada, 2013). The difference between the two ranges is expected to be due to the difference in the tilt angles, measurement approaches, the amount of collected data, and the effect of the light bird droppings in the collected data of this study.

10- CONCLUSION

The soiling loss for six PV systems in the Phoenix Metropolitan area has been evaluated. The study included five cities: Gilbert, Chandler, Mesa, Phoenix, and Goodyear. Monthly and daily soiling loss maps were generated for the Phoenix Area. The following conclusions were drawn from the results of the study:

1. The daily soiling rate found in the first part of the thesis, -0.061% was validated since it falls within the range of the daily soiling rates found in the second part of the thesis, -0.057% to -0.085%.
2. For tilt angles of 13° to 28°, the monthly soiling rate, without considering the effect of heavy bird droppings, in the Phoenix area ranges from -1.71% to -2.55%, with an average of -1.99%.
3. Soiling rates in the East valley appear to be higher than the Central and West valleys. The average monthly soiling rate in the East valley was found as -2.23%, against -1.71% in the Central valley and -1.78% in the West valley. However, it is to be noted that these rates have been reported based only a very systems. To increase confidence in this data, more number of systems is recommended to be included.
4. Heavy bird droppings were noticed more in the East valley than the Central and West valleys, resulting in very high soiling losses. However, it is to be noted that these rates have been reported based only a very

systems. To increase confidence in this data, more number of systems is recommended to be included.

5. The Monthly Soiling Rates (MSR) for systems with High Bird Droppings (HBD) are much higher than the systems with no or Low Bird Droppings (LBD). That was noticed in a Chandler system with as high as 81% instantaneous loss due to HBD coverage on a single cell of a module/string. The HBD system had -6.08% MSR, while the LBD systems had -2.55%.
6. Higher soiling losses were usually noticed accompanied with the following conditions: heavy bird droppings, lack of rain for a long period, low tilt angels, and low cleaning frequencies.
7. Tall surroundings around the PV arrays, like trees and buildings, were noticed as a good preventive approach for mitigating the soiling losses.
8. The average water consumption of cleaning the PV modules was found almost 1.5 liter/m^2.

From the results and conclusions found in this study, the following recommendations are suggested for the public:

1. The soiling loss map, presented in this study, may be adopted by the PV systems designers, installers, owners, and operators.
2. For PV modules with high bird droppings, increasing the cleaning frequency is recommended to avoid the big loss of the generated PV

power. Installing bird spikes would also be a good idea for keeping the birds away from the PV modules.

For improving this study in the future, the following suggestions are presented for future researchers:

1. More soiling data should be collected for different cities in the Phoenix area, for improving the soiling loss mapping and generating more statistically relevant figures of location-specific soiling losses.
2. More quantitative data and analysis is needed for studying the bird droppings effect on the performance of the PV modules.
3. The dust sampling method, used in this study, should be validated with additional data collection for its repeatability.
4. The second round of this study should be done during the period between March to July for two reasons:
    a. First, most of the cleaning jobs of PV systems are done in this period.
    b. Secondly, the dust deposition in this period is almost steady and linear because of the absence of the dust storms in which the dust deposition becomes abnormally high. Collecting soiling data in the summer period helps in obtaining more accurate soiling rate.

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APPENDIX A

THE PROJECT PLAN OF THE ROOFTOP STUDY

Date	Task	Notes
5/1/2014 (May 1st /2014)	Starting the system	Daily cleaning for reference cell and module 12
Last week of May	Collect AOI data for Module 17 (soiled)	Clear sky
6/2/2014 (June 2nd /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean module 17	- Clean at noon (clear sky) - From now on, module 17 will be monthly washed
First week of June	Collect AOI data for Module 17 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= monthly (find the soiling loss) - AOI results, Reflectance, soiling density - Soiling modelling - Climatological relevance - Dust Accumulation Rate	
6/15/2014 (June 15th /2014)	- Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean module 22	- Clean at noon (clear sky)
Last week of June	Collect AOI data for Module 13 (soiled)	Clear sky
7/1/2014 (July 1st /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 13, 17 - For module 17: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky) - From now on, module 13 will be washed every two months
First week of July	Collect AOI data for	Clear sky

	Module 13 (clean)	
After above-mentioned	Data processing and analysis - CF= every month and a half (module22) every 2 months (module13)- (find the soiling loss) - AOI results (module 13), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of module 17	
7/15/2014 (July 15th /2014)	- Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean module 16	- Clean at noon (clear sky)
Last week of July	Collect AOI data for Module 9 (soiled)	Clear sky
8/1/2014 (August 1st /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 9, 17 - For module 17: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky) - From now on, module 9 will be washed every three months
First week of August	Collect AOI data for Module 9 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 2and a half months (module 16) every 3 months (module 9) – (find the soiling loss) - AOI results (module 9), Reflectance, soiling	

	density - Soiling modelling - Climatological relevance - Include results of module 17	
8/15/2014 (August 15th /2014)	- Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean module 19	- Clean at noon (clear sky)
Last week of August	Collect AOI data for Module 10 (soiled)	Clear sky
9/1/2014 (September 1st /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 10, 17, 13 - For modules 17, 13: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky) - From now on, module 10 will be washed every 10 months
First week of September	Collect AOI data for Module 10 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 3and a half months (module 19) every 4 months (module 10) – (find the soiling loss) - AOI results (module 10), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17, and 13	
9/15/2014 (September 15th /2014)	- Dust Sampling, fill SCS, write down the cleaning time, take	- Clean at noon (clear sky)

	pictures - Clean module 7	
Last week of September	Collect AOI data for Module 1 (soiled)	Clear sky
10/1/2014 (October 1st /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 1, 17 - For modules 17: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky) - From now on, module 1 will be washed every 5 months
First week of October	Collect AOI data for Module 1 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 4 and a half months (module 7) every 5 months (module 1) – (find the soiling loss) - AOI results (module 1), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17	
Last week of October	Collect AOI data for Module 14 (soiled)	Clear sky
11/1/2014 (November 1st /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 14, 17, 13, 9 - For modules 17, 13, and 9: Dust Sampling, fill SCS, write down the cleaning time,	- Clean at noon (clear sky) - From now on, module 14 will be washed every 6 months

	take pictures (No AOI, or reflectance)	
First week of November	Collect AOI data for Module 14 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 6 months (module 14) – (find the soiling loss) - AOI results (module 14), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17, 9 and 13	
Last week of November	Collect AOI data for Module 8 (soiled)	Clear sky
12/1/2014 (December 1st /2014)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 8, 17 - For module 17: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky)
First week of December	Collect AOI data for Module 8 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 7 months (module 8) – (find the soiling loss) - AOI results (module 8), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17	

Last week of December	Collect AOI data for Module 20 (soiled)	Clear sky
1/1/2015 (January 1st /2015)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 20, 17, 13, 10 - For modules 17, 13, and 10: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky)
First week of January	Collect AOI data for Module 20 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 8 months (module 20) – (find the soiling loss) - AOI results (module 20), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17, 10 and 13	
Last week of January	Collect AOI data for Module 21 (soiled)	Clear sky
2/1/2015 (February1st /2015)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 21, 17, 9 - For modules 17, and 9: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or	- Clean at noon (clear sky)

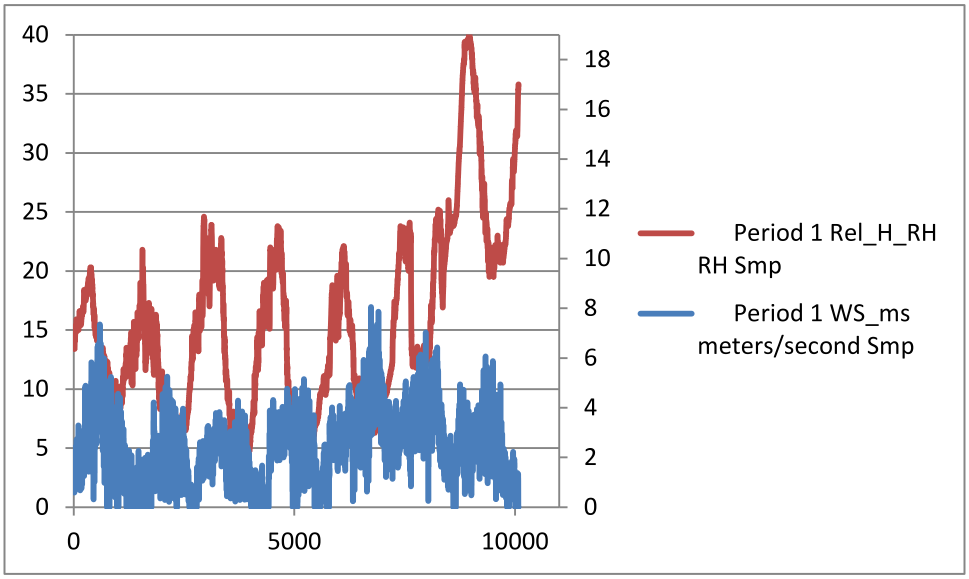
	reflectance)	
First week of February	Collect AOI data for Module 21 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 9 months (module 21) – (find the soiling loss) - AOI results (module 21), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17, and 9	
Last week of February	Collect AOI data for Module 23 (soiled)	Clear sky
3/1/2015 (March 1st /2015)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 23, 17, 5, 13 - For modules 17, 5, 13: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky)
First week of March	Collect AOI data for Module 23 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 10 months (module 23) – (find the soiling loss) - AOI results (module 23), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17, 5, and	

	13	
Last week of March	Collect AOI data for Module 15 (soiled)	Clear sky
4/1/2015 (April 1st /2015)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 15, 17 - For module 17: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky)
First week of April	Collect AOI data for Module 15 (clean)	Clear sky
After above-mentioned	Data processing and analysis - CF= every 11 months (module 15) – (find the soiling loss) - AOI results (module 15), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of module 24	
Last week of April	Collect AOI data for Module 11 (soiled)	Clear sky
5/1/2015 (May 1st /2015)	- Reflectance, Dust Sampling, fill SCS, write down the cleaning time, take pictures - Clean modules 11, 17, 13, 9, 10, 14 - For modules 17, 13, 9, 10, 14: Dust Sampling, fill SCS, write down the cleaning time, take pictures (No AOI, or reflectance)	- Clean at noon (clear sky)
First week of May	Collect AOI data for	Clear sky

	Module 11 (clean)	
After above-mentioned	Data processing and analysis - CF= every 12 months (module 11) – (find the soiling loss) - AOI results (module 11), Reflectance, soiling density - Soiling modelling - Climatological relevance - Include results of modules 17, 13, 9, 10, 14	

APPENDIX B

READINGS OF THE RH AND WS OF THE ROOFTOP EXPERIMENT



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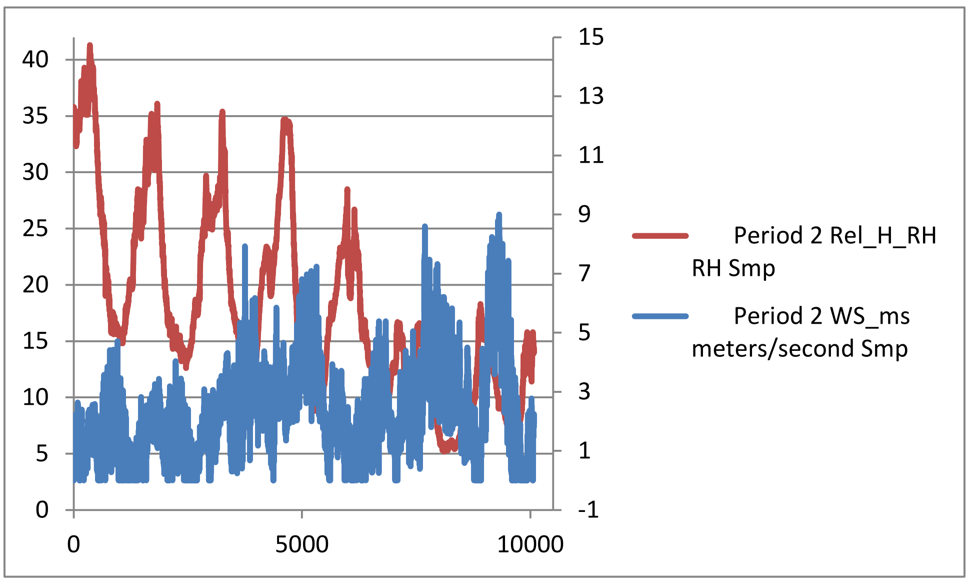
Period 1 WS_ms meters/second Smp



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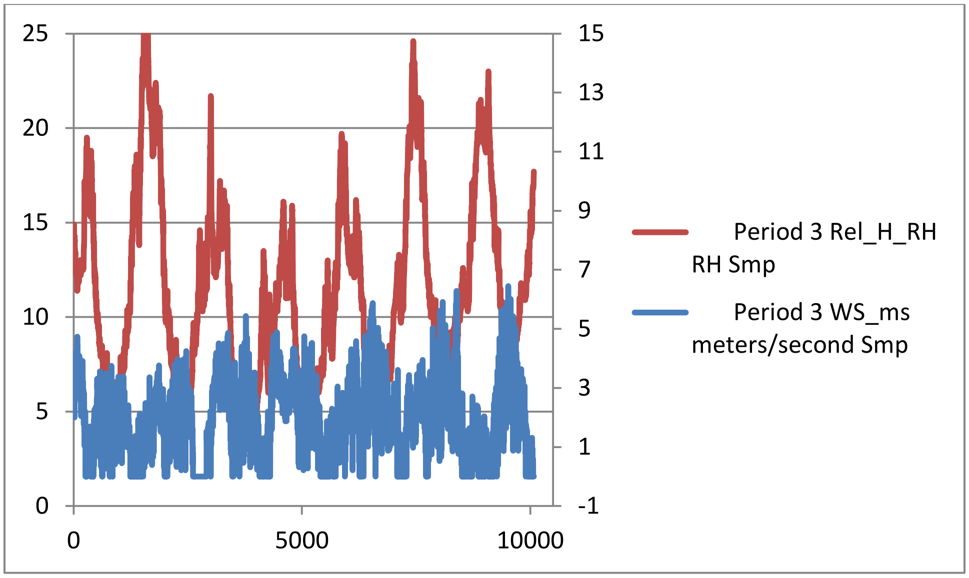
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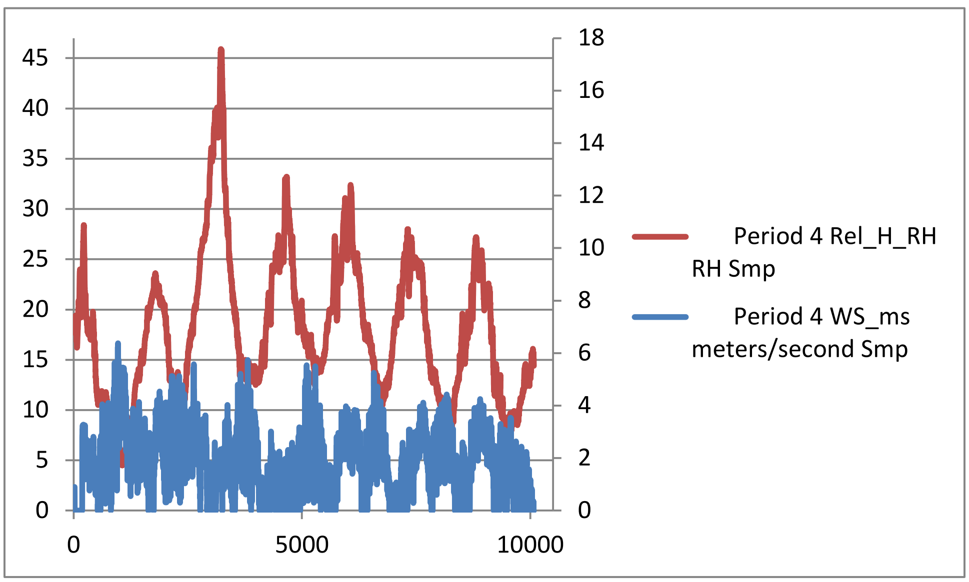
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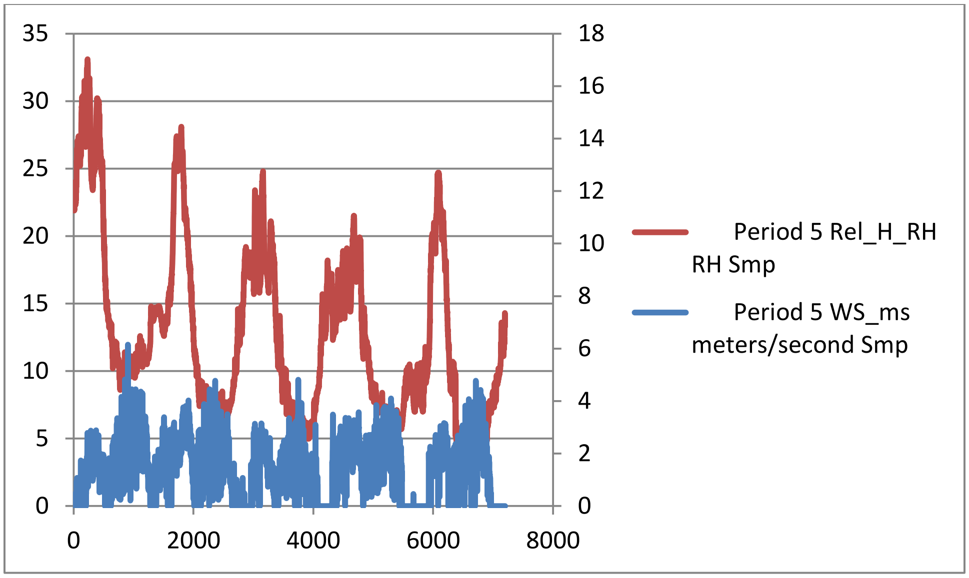
Period 4 Rel_H_RH RH Smp
Period 4 WS_ms meters/second Smp



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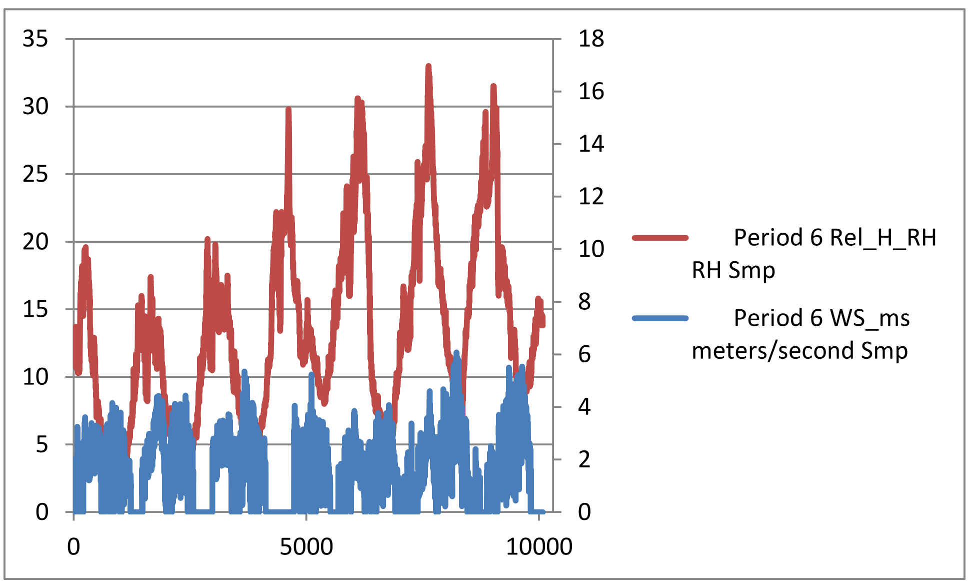
Period 5 Rel_H_RH RH Smp
Period 5 WS_ms meters/second Smp



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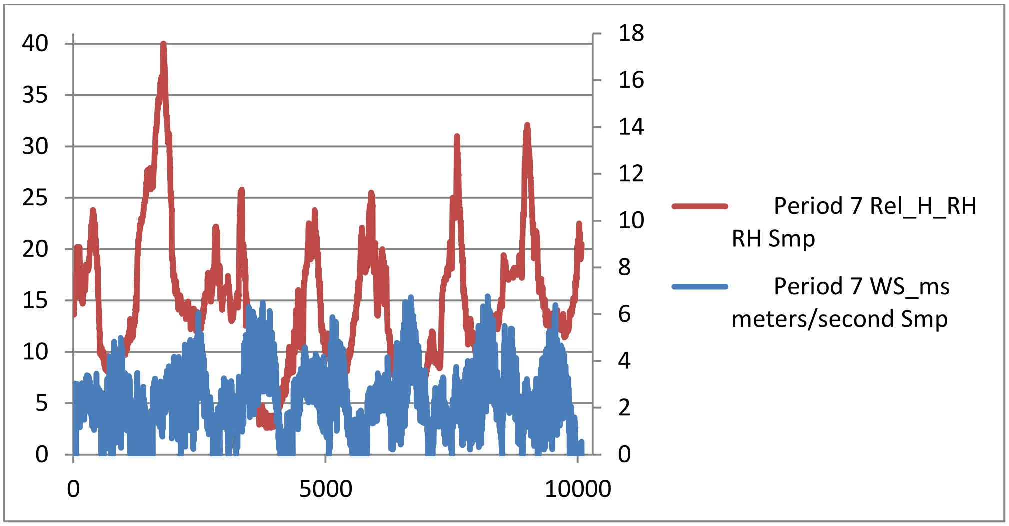
Period 6 Rel_H_RH RH Smp
Period 6 WS_ms meters/second Smp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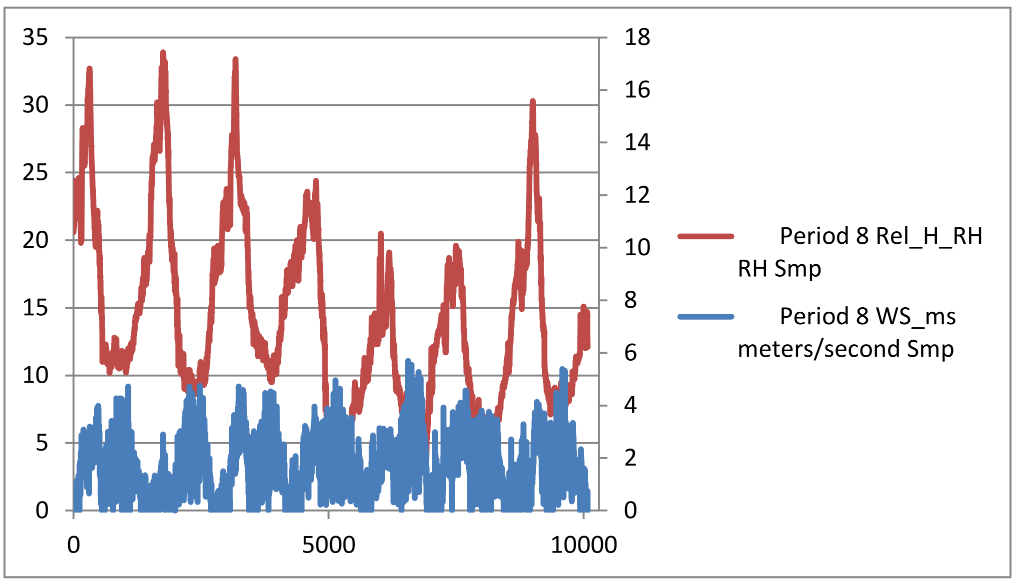
Period 7 Rel_H_RH RH Smp
Period 7 WS_ms meters/second Smp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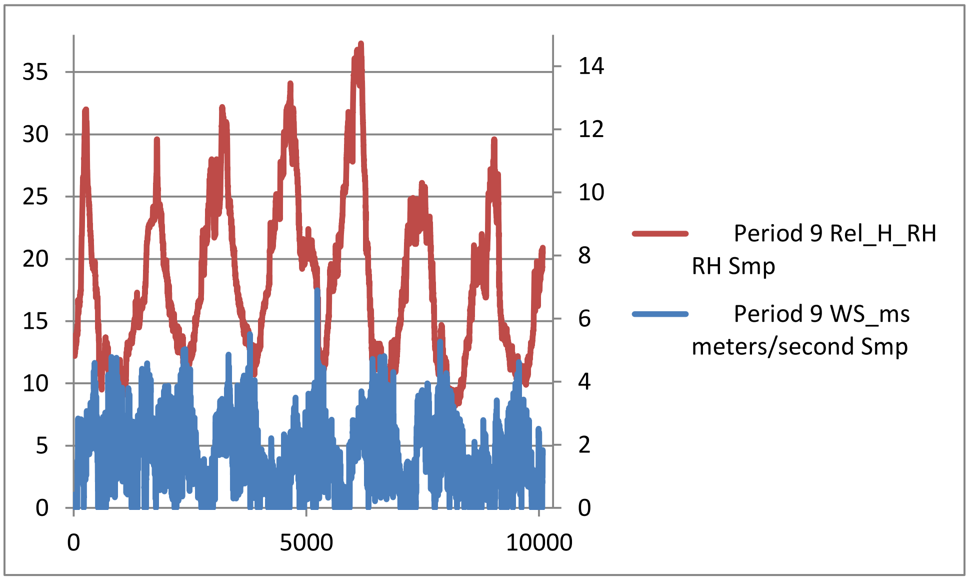
Period 8 Rel_H_RH RH Smp
Period 8 WS_ms meters/second Smp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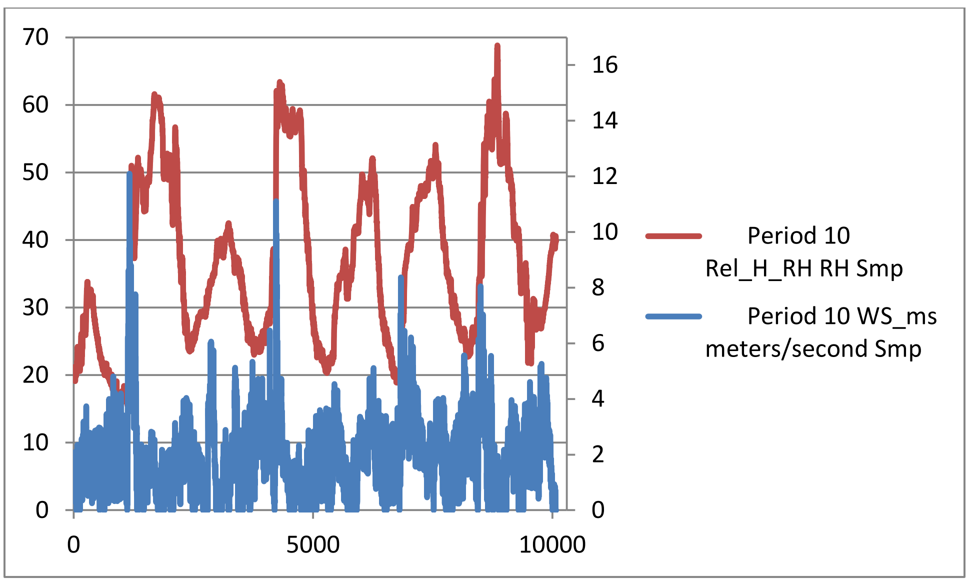
Period 9 WS_ms meters/second Smp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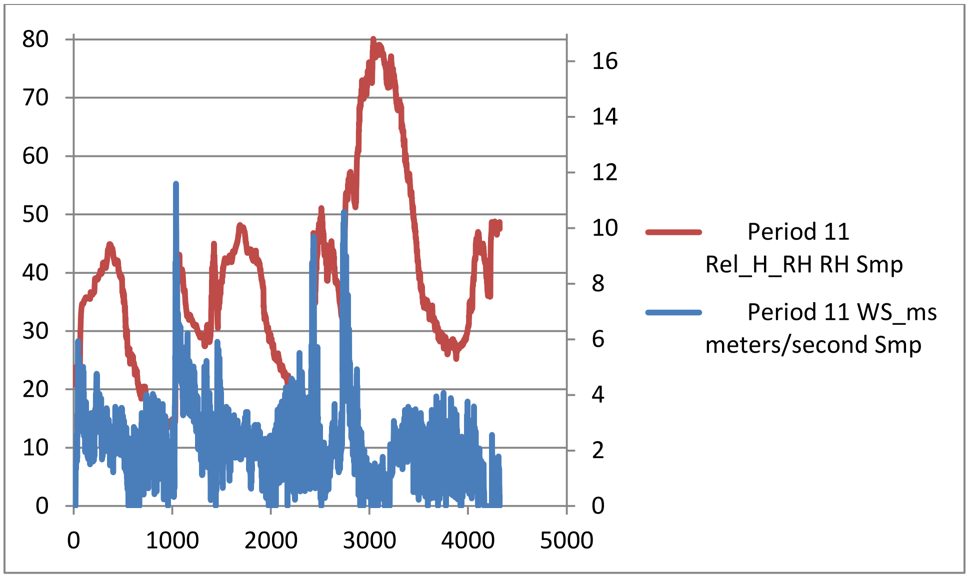
Period 10 WS_ms meters/second Smp



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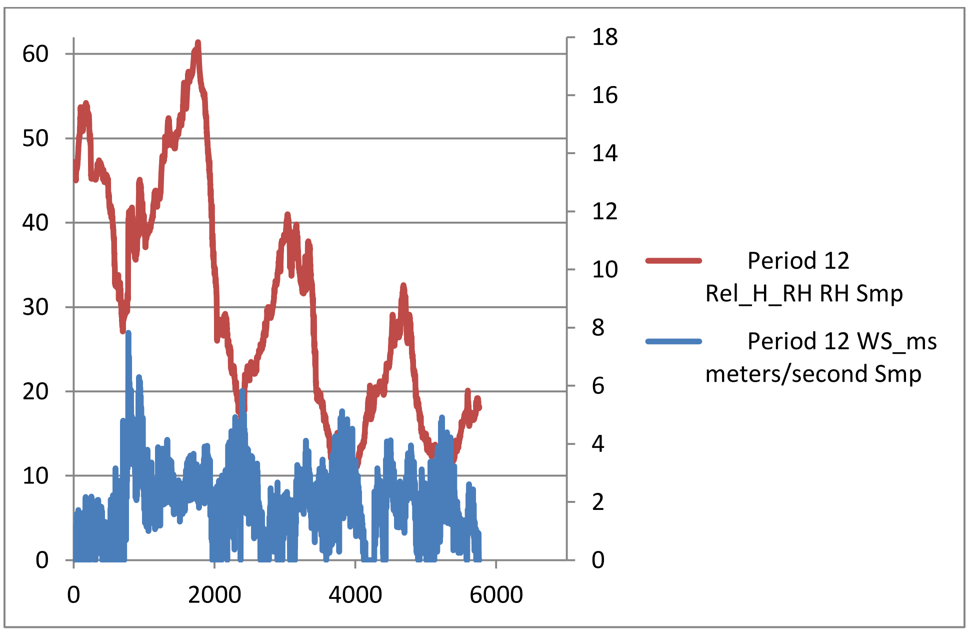
Period 11 Rel_H_RH RH Smp
Period 11 WS_ms meters/second Smp



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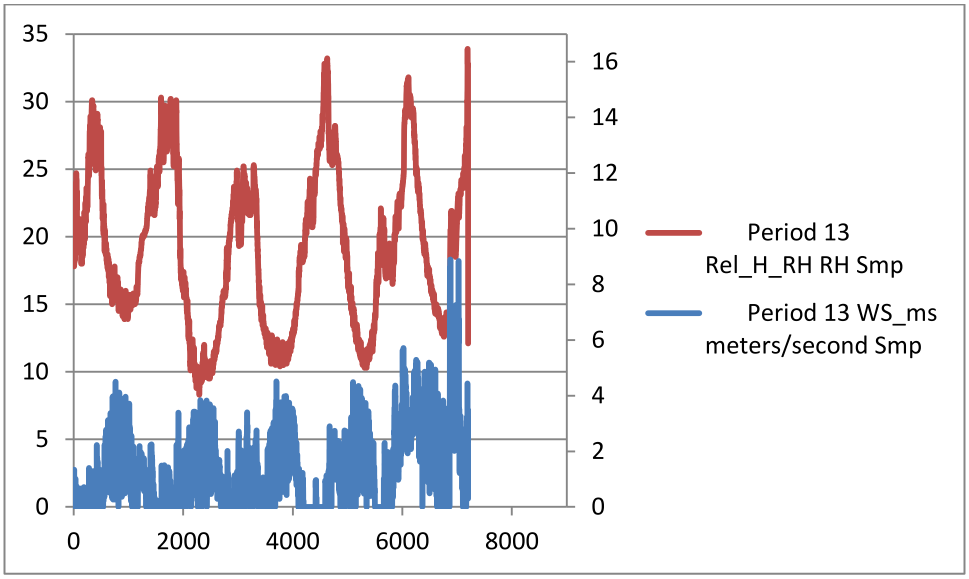
Period 12 Rel_H_RH RH Smp
Period 12 WS_ms meters/second Smp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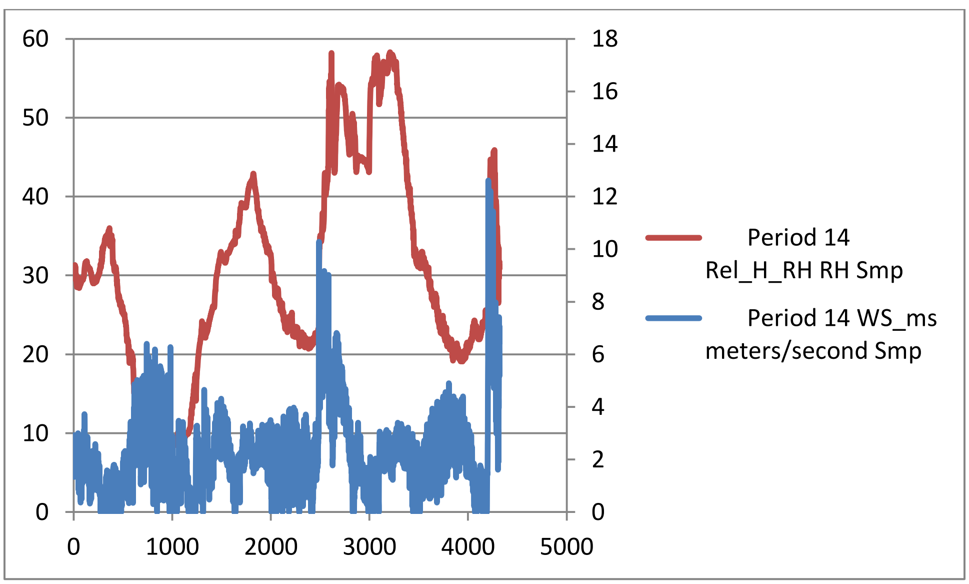
Period 13 Rel_H_RH RH Smp
Period 13 WS_ms meters/second Smp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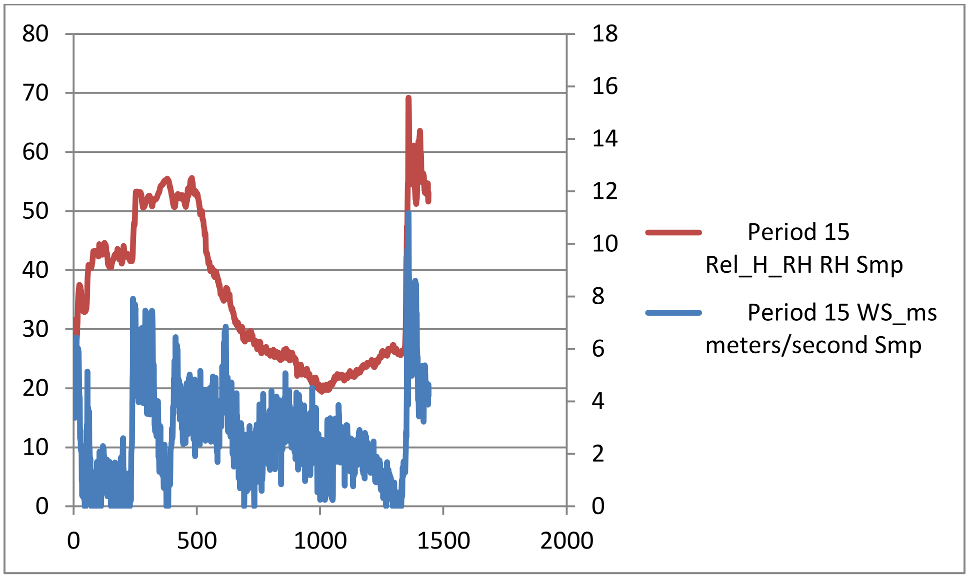
Period 14 WS_ms meters/second Smp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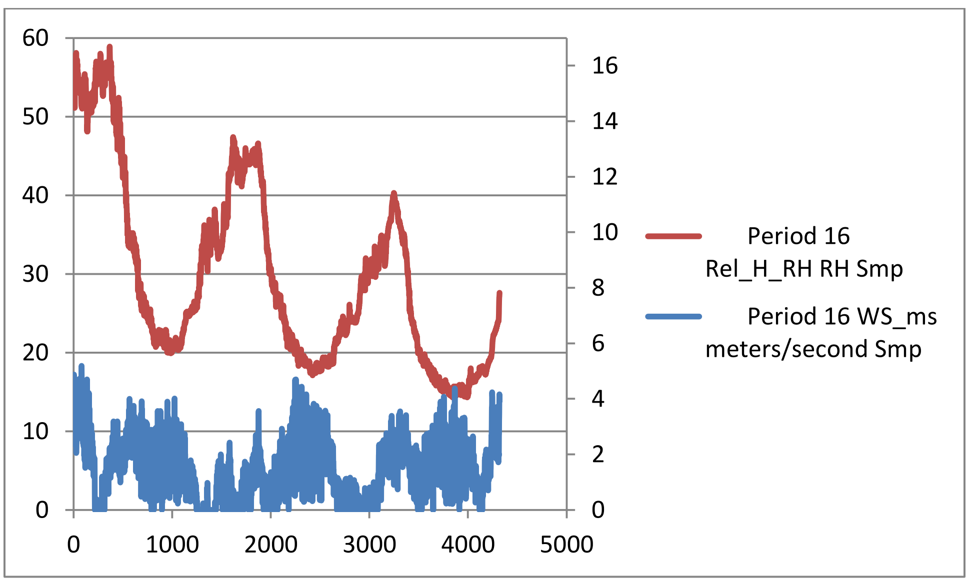
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Period 16 Rel_H_RH RH Smp
Period 16 WS_ms meters/second Smp

APPENDIX C

CHECKLIST FOR EVALUATING THE SOILING EFFECT ON THE PERFORMANCE OF PV MODULES IN THE STATE OF ARIZONA

1. **General Information**

Name of the cleaning company: ________________________________

Job number: _______ Date and time of current cleaning: ___________

Date of last cleaning (if applicable): _________________

Cleaning service frequency: ☐ One-time ☐ Semi-annual ☐ Other: _____

Location (full address or nearest major cross-streets): _______________

_____________________________________City: _______________

The location is in or nearby: ☐ City area ☐ Downtown area ☐ Rural area

☐ Industrial area ☐ Agricultural area ☐ Bad traffic area ☐ Desert area

2. **PV System Information**

PV system type: ☐ Residential ☐ Commercial ☐ Utility-scale

Number of modules in the PV system: ___ Number of modules per string: ___

Dimensions (length x width) of one PV module (cm^2 or ft^2): _____X_____

PV array level: ☐ Ground ☐ 1-story rooftop ☐ 2-story rooftop ☐ Other:____

The PV array is surrounded by: ☐ Gravels ☐ Grass ☐ Fence ☐ Trees ☐ None

PV mounting system: ☐ Flat ☐ Fixed-tilted ☐1-axis tracker ☐ 2-axis tracker

If fixed tilt, the tilt angle (degree): ______

3. **Before Cleaning**

Reference cell reading (mV): ______ String Operating current (amperes): _____

PV module temperature (°C): __________

Inverter P_{ac} (watts): __________ Inverter V_{pv} (volts): __________

Inverter energy reading (kWh): ___________ Inverter current (Amps): _______

Reference cell reading (mV): ___________

Bird droppings: ☐ No ☐ Low ☐ High

Take Following Pictures: ☐ The PV array ☐ Soiled PV module (Close-up)

☐ Modules' Nameplate

4. **Dust Sampling**

Take 3 samples using the reusable lint roller.

Number of sampling squares used: _____

5. **<u>After Cleaning</u>**

Reference cell reading (mV): _____ String Operating current (amperes): ____

PV module temperature (°C): _________

After having the PV module's temperature stabilized …

Inverter P_{ac} (watts): __________ Inverter V_{pv} (volts): ___________

Inverter energy reading (kWh): _____________ Inverter current (Amps): _________ Reference cell reading (mV): ___________

Water consumed for cleaning the whole PV system (liter/gallon): ___________

Cleaning duration: ____________

Any detergent used: ☐ Yes ☐ No

Cost of cleaning ($): ____________

APPENDIX D

SOILING TESTING TOOLKIT (STT) FLYER

Soiling Testing Toolkit (STT)

Instrument A: Measuring Tape

Function: to measure the dimensions (width and length) of the module. It is also used to measure the dust sampling area.
How to use: take the measurements of both long and short sides of the module.
Notes: readings could be either in centimeters or feet. Circle one of those units while filling the soiling checklist sheet.

Instrument B: Inclinometer

Function: to measure the tilt angle of the solar module.
How to use: place the device onto the top surface of the solar module, and then write down the reading in the soiling checklist sheet.

Instrument C: Compass

Function: to measure the direction of the PV array.
How to use: 1) make sure you are using it while away from any iron-made objects. 2) place the compass onto the PV module, as shown above, and point the arrow to the direction of the PV array (or module). 3) turn the compass dial until “N” aligns with the red end of the needle and “S” aligns with the white end. 4) read the array direction in degrees, and then write down the reading in the soiling checklist sheet.
Notes: if the PV array is south facing, write down “S” in the soiling checklist sheet.

Instrument D: Solar Meter

Function: to measure the solar irradiance in Watts/m^2.
How to use: switch on the device, hold it next to one of the modules of the test string as shown above, and then write down the reading in the soiling checklist sheet.
Notes: avoid dropping the meter. Keep the device in a cool and dry place while not in use.

Instrument E: Clamp-on Meter

Function: to measure the electric current flowing in the test module in amperes.
How to use: 1) set the function switch to the DCA range. 2) press the ZERO key to null the meter display. 3) press the trigger to open the current sense Jaw. 4) fully enclose the conductor to be measured. Do not allow a gap between the two halves of the jaw. 5) read the DCA value on the LCD and write it down in the soiling checklist sheet.

Notes: 1) do not shadow the modules during measuring 2) never operate the meter unless the back cover and the battery/fuse door are in place and fastened securely. 3) enclose only one wire (not two or more.)

Instrument F: Infrared (IR) Thermometer

Function: to measure the module and ambient temperatures.
How to use: 1) point the meter toward an active blue spot in the module (7 inch away of the module surface.) 2) pull and hold the trigger to turn the meter on and begin testing. 3) release the trigger and the reading will hold for approximately 10 seconds. 4) write that reading down in the soiling checklist sheet.

Notes: in case of measuring the ambient temperature, point the meter toward a shaded white object, and then follow steps 2 to 4 again.

Instrument G: Sampling Tools

Function: to collect samples of the dust accumulated on the PV modules.
How to use: 1) roll the lint roller over the sampling area 2) using the measuring tape, measure the sampling area and write it down in the soiling checklist sheet. 3) remove the used sheet from the lint roller, fold it, and put it into a Ziploc bag. 4) mark the sample (N: north sample, E: east sample, S: south sample, and W: west sample)

Notes: seal the sample very well.

APPENDIX E

STANDARD OPERATING PROCEDURE (SOP) FOR DUST SAMPLING USING WASHABLE LINT ROLLERS

Applications

This procedure shall be used in all indoor and outdoor dust sampling from the top surface of the solar modules.

Procedure

1- Using a microbalance, measure the mass of the roller and write it down as **m1** in Table.1.


2- Put the roller in the Ziploc bag, seal the bag well, and mark it.

3- If it is outdoor sampling, do it after 10:00 a.m. To start sampling, take the roller out of the bag and roll it on a predefined sampling area (A) within the top surface of the solar module. Roll it both vertically and horizontally as shown below. Write down the sampling area **(A)** in the table.1.


4- Immediately after sampling, put the roller back into the Ziploc bag and seal it very well.

5- Again using the microbalance, measure the mass of the roller after sampling, and write it down as **m2** in the table.1.

6- Using table.1, calculate the soiling density for sample 1 **(SD1)**.

7- Do the same above steps again for samples 2, 3, and 4 to get **SD2, SD3, and SD4**, respectively.

8- Complete filling table.1 to get the Average Soiling Density **(ASD)**.

Table.1 Calculating the Average Soiling Density (ASD) from the dust samples

Sample 1			
m1 (g)=	m2 (g)=	A (cm^2)=	
SD1 (mg/m^2)= $10^7 \times \frac{m2-m1}{A} =$			
Sample 2			
m1 (g)=	m2 (g)=	A (cm^2)=	
SD2 (mg/m^2)= $10^7 \times \frac{m2-m1}{A} =$			
Sample 3			
m1 (g)=	m2 (g)=	A (cm^2)=	
SD3 (mg/m^2)= $10^7 \times \frac{m2-m1}{A} =$			
Sample 4			
m1 (g)=	m2 (g)=	A (cm^2)=	
SD4 (mg/m^2)= $10^7 \times \frac{m2-m1}{A} =$			
Average Soiling Density (ASD) - for all above samples			
SD1 (mg/m^2)=	SD2 (mg/m^2)=	SD3 (mg/m^2)=	SD4 (mg/m^2)=
ASD (mg/m^2)= $\frac{SD1+SD2+SD3+SD4}{4} =$			

Notes

To reuse the rollers, wash with warm water and dish soap, and then let dry (put in the oven on 30°C for 3 hours).