UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

A FEASIBILITY STUDY ON THE EFFECT OF SOILING ON THE PERFORMANCE OF SOLAR PV WATER PUMPING SYSTEMS IN NAIROBI.

BY

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A Thesis Submitted in Partial Fulfillment for the Award of Master of Science Degree in Energy Management of the University of Nairobi.

2017

DECLARATION

This thesis is my original work and has not been submitted for the award of a degree in any other University

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Signature Date

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Supervisors

This thesis has been submitted for examination with our approval as University Supervisors.

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Signature Date

1. Prof. Abungu

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Signature Date

2. Dr. Mwema

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Dedication

I dedicate this work to my family and friends who have always been there to support me. Without them, this work would not have been possible.

Acknowledgement

First, I would like to thank the almighty God for the gift of life and good health throughout my study. Without him, this work would not have started let alone be completed.

I would also like to express my deepest gratitude to the patience, diligence and resourcefulness accorded to me by my supervisors: Prof. Abungu and Dr. Mwema. Not only did they provide invaluable guidance and constructive criticism during my studies but also listened to my idea and gave me immensurable advice when formulating the proposal, during experimentation and when writing the final thesis.

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List of Abbreviations

p^+	p-dopant material
p^+	n-dopant material
V_{oc}	Open circuit voltage (volts, V)
I_{sc}	Short circuit current (amperes, A)
E_g	energy gap
V_{mp}	Maximum voltage (volts, V)
I_{mp}	Maximum current (amperes, A)
V_{mp}	Maximum power (W)
FF	Fill Factor
η	Efficiency
P_{out}	Output Power from PV module (W)
P_{in}	Input Power from light
I_o	Reverse saturation current (ampere,A)
I_{max}	Maximum output current (amperes,A)
I_{ph}	Photon current (amperes, A)
q	Electronic charge, (coulomb,C)
n	Ideality factor,
k	Boltzmann constant (joules per kelvin,$J.K^{-1}$)
T	Temperature (degrees celsius °C)
STC	Standard Test Conditions
ARC	Anti Reflection Coating
R_s	Series resistance (ohms, Ω)
R_{sh}	Shunt Resistance (ohms, Ω)
CSP	Concentrated Solar Power

a-Si	Amorphous silicon
c-Si	Crystalline silicon
CIGS	Copper Indium Gallium Selenide
CdTe	Cadmium Telluride
EQE	External Quantum Efficiency
CL	Confidence Level
ANOVA	Analysis of Variance
α	significance level = 0.05
PSI (psi?)	Pound per square inch
TA	Tilt Angle

ABSTRACT

The soiling effects on solar photovoltaic modules and solar water pumps are of great concern in countries with large generation potential for solar energy. Previous studies indicate that soiling affects the PV performance. No previous studies on soiling impacts in Kenya as well as their influence on solar water pumping have been conducted. In this project, the cumulative effects of dust accumulation were investigated for a period of 90 days. Two sites in Nairobi; Karen and industrial area were selected. The soiling impact affected key performance metrics and this was used to conduct a comparative analysis between clean and soiled panels as well as modules at different tilt angles and location. The results indicate that cumulative soiling considerably reduced the power output of the soiled panel as compared to the cleaned one (12% reduction). Low tilt angle was also found to promote dust accumulation (11.9% less for module at 10°). Soiling was found to reduce the efficiency of the module from 10.5 % to 7.26% (15° tilt angle) and 6.3% (10° tilt angle) for the first 25 days and this further reduced to 4% (15° tilt angle) and 4.22% (10° tilt angle). Soiling losses were found to increase with cumulative dust adherence over the study period and were affected by the tilt angle. The fill factor was also affected by soiling. The cleaned module had a FF = 0.81 while the soiled module had FF= 0.70(13% less) in the first month and 0.52 (34.8%) in the last month. Soiling was also found to cause significant loss in rectangularity of the I-V curves and this increased with more dust accumulation. Dust accumulation was affected by the location. The industrial area site recorded lower power, efficiency and increased soiling losses as compared to the Karen site. The pump performance was found to reduce with increase in soiling over the entire study period. Dust accumulation significantly reduced flow rate and maximum head and altered the shape of performance curves (Q-H curves). It is recommended that a correction factor be introduced when designing and sizing PV panels in Kenya and regular cleaning to reduce these effects.

CHAPTER 1

INTRODUCTION

1.1 Background to the study

Solar photovoltaic (PV) is one of the most important renewable energy in the world. It is becoming a principle source of power in grid and off grid systems all over the world. In terms of installed capacity, it is ranked third after hydropower and wind. As of 2014, the global installed capacity was 177 GWh (International Energy Agency, 2014). PV therefore represents one of the next generation renewable energy sources due to its high reliability during the day and prevention of global pollution, climate change and reduction in greenhouse gas emissions. (Bayod-Rújula, Ortego-Bielsa, & Martínez-Gracia, 2010).

The performance of PV modules depends upon the geographical factors (longitude, latitude, and solar intensity), the environmental factors (temperature, wind, humidity, pollution, dust, rain, etc.) and the type of PV technology used. These factors affect the intensity of sunlight energy which in turn reduces the efficiency and power output of the PV.

Most commercial solar cells have an efficiency that ranges between 15-20%. Various technologies such as mono-crystalline, polycrystalline, thin film and transparent solar cells have varying efficiencies and performance curves which are also affected by the environmental conditions. Most researches on solar PV have focused on increasing efficiency through changing the tilt angle, increasing the exposure using sun tracers and sun tracking systems and reducing the impact of temperature. Dust, shading, bird droppings and other factors which considerably reduce the performance and efficiency of most PV cells in most parts of the world have not received considerable attention.

Dust is one of the major environmental factors affecting the performance of PV cells. These are minute solid particles with diameters less than 500 µm accumulating on the PV. The air quality is considerably aggravated by suspended particles that may be directly emitted from both human and natural processes or formed in the atmosphere. These particles include sand, silt, soil, clay, minerals, pollutants from factories and vehicles and chemicals (Ramanathan & Feng, 2009). They also include particulate matter (PM) consisting of finely subdivided solids or liquids such as dust (e.g. particles deriving from civil construction activities), fly-ash, smoke, aerosols and condensing vapors (Mani & Pillai, 2010).

The mechanism through which dust accumulates is complicated and dependent on many design and environmental factors. The characteristics of dust settlement on a PV systems are dictated by two primary factors that influence each other: the property of dust and the local environment. The property of dust refers to the physical, chemical, biological, electrostatic properties that influence the rate of its accumulation on the PV. These factors necessitate site specific tests to be carried out since dust characteristics vary at different localities. For example, soil particles with high electrostatic properties are likely to stick more on PV plate as compared to those with lower ability to be charged (Shaharin, Haizatul, Hussain, & Mohd, 2011). The local environment refers to site-specific factors which have great impact on dust accumulation. First, prevailing human activities such as construction, agricultural activities such as farming loosen the soil and these increase deposition rate. Industrial emissions in large towns deposit soot and ash at a high rate which subsequently affects the performance of these cells. Sun and windy areas are likely to induce more deposition due to loosening and easy transportation of dust particles. Highly populated areas which have high air pollution, smoke, soil, pollen grains, high vehicular movement, vegetation, fabric pieces, fungi spores present in the atmosphere are also likely to accelerate the deposition process (Mani & Pillai, 2010).

1.2 Statement of the problem

Soiling reduces the amount and intensity of light incident on the actual silicon cells inside the module. The rate of soiling is dependent on local climatic conditions (humidity, rainfall, wind, etc.) as well as the composition of dust particles in the air. Depending on the geographic location and PV system configuration, the loss of power due to soiling has been reported to range from 1% to 20%. However, other studies have shown annual soiling losses as high as 14% (Canada, 2013), monthly soiling losses as high as 20% (Hutchinson, 2000) and short-term soiling losses as high as 30% (Zorrilla-Casanova, Piliougine, Carretero, & Bernaola, 2011). As a result, many MW-scale PV system owners believe it is economical to wash their systems several times a year (Hammod, 1997).

Although many studies on soiling have been conducted, there have been no studies on soiling undertaken in East Africa and particularly Kenya. There was general lack of pertinent data that can be used by researchers and solar installation companies in the design and installation of these panels. Lack of this data means that most users do not clean their panels and this leads to a decrease in efficiency and power output. Furthermore, designers and solar installation firms are unable to recommend on the number of cleaning cycles on solar installation as no quantitative data is available to recommend a correction factor.

1.3 Objectives

1.3.1 Main objectives

The main objective of this work was to study the effects of soiling on the performance of PV panels and in solar water pumping systems located in Nairobi in order to optimize their performance, increase efficiency and maximize power output and utilization of these pumps. To achieve this objective, the following specific objectives were accomplished.

1.3.2 Specific objectives

a) Development of an experimental setup to measure and compare the power output of two sets of identical PV modules. One module was cleaned on a weekly basis while the other two were not cleaned. Two identical unclean modules were adjusted to a tilt angle of 10 and 15 degrees.

b) Determination of the effects of soiling on the performance of solar PV based on the current –voltage response (I-V curve), V_{oc}, I_{sc} Power, fill factor, efficiency and soiling losses of study PV panels.

c) Determination of the soiling effects on the performance of solar water pumping systems based on the output (Q-H) of a solar water pumping system in Nairobi.

1.4 Justification of the study

PV modules convert solar irradiation into electricity through photoelectric effect and are placed outdoors where they are subject to soiling. Settling of small particles on the transparent surface of the modules causes obstruction of light hence reducing the solar irradiation falling on the surface of the cell. The remaining light throughput is lower and the module power output will drop proportionally. The reduction in power from the particulates built up can be over 10%. Wet weather causes a self-cleaning effect, however in dry climates (desert areas) cleaning has to be taken seriously. Determining the effects of soiling was imperative to improving the performance of PV panels.

1.5 Study scope

The scope of this research was limited to studying the effects of soiling on the expected performance of PV modules of a solar water pumping system installed in Nairobi and the overall effect that cleaning had on improving their performance.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The basic unit of a photovoltaic system is the photovoltaic cell. The term photovoltaic means the direct conversion of light into electrical energy. Photovoltaic effect is the establishment of an electric field in a material through absorption of optical energy. Over the years, researchers have developed different cells to generate electrical energy from light.

2.2 Losses in solar PV cells

The main losses observed in solar cells have been documented by various researchers and include:

Electrical Loses - Two main electrical losses include parasitic resistance and recombination (Bayod-Rújula, Ortego-Bielsa, & Martínez-Gracia, 2010).

Reflection- This occurs when incident photons are reflected by the cell surface. This problem is eliminated through surface texturing and use of anti-reflection coating (ARC) (Alexander, 2014).

Shading losses - The presence of partial shade on the module surface will result in dramatic output reduction (Boxwell, 2013). Some PV modules are affected more by shading than others (Garcia, Marroyo, Lorenzo, & Perez, 2011).

Incomplete absorption- Photon energy of the incident radiation must be greater or equal to the energy gap width for absorption to occur. If the photon energy is much greater than the gap energy, absorption is confined to the surface region of the material.

Resistive Losses - The resistive losses are the result of series R_s and shunt resistances $R_{sh}$of a solar cell. These two resistances affect the final FF of solar cell.

Recombination Loss -When illuminated, the generation of electron-hole pairs occurs throughout a silicon solar cell. The excess carriers return back to reach a thermal equilibrium by recombination of excess electrons and holes (Boxwell, 2013) (Kimber, Mitchell, Nogradi, & Wenger, 2006).

Soiling-The accumulation of dust, dirt, pollen and other environmental contaminants on PV modules result in the reduction of solar irradiance reaching the solar cells hence reduced power output from the modules (Hussein, Tamer, Sopian, Buttinger, Elmenreich, & Ahmed, 2013).

2.2 Previous Works Relevant To the Study

2.2.1 Effects of soiling on PV modules

Many researchers have studied various aspects of PV soiling and dust accumulation. Kimber et al (Kimber, Mitchell, Nogradi, & Wenger, 2006) investigated the effect of soiling for large grid-connected PV systems in California and US Southwest region. Decline in the systems performance throughout the dry season was practically linear, although systems, while being put in similar conditions, did not show the same performance recovery and degradation patterns.

Muhammad el al (Mohammad and Fahmy, 1993) studied the effect of the physical properties of dust (mainly particle size), and their influence of the amount of dust on the output of a solar panel. Their work showed that smaller particles have a far greater effect than larger particles on the transmittance through glass (Mohammed & Fahmy, 1993). A paper based on a study conducted by ASU concluded that 0.2 inch of rain was nearly equivalent to physically cleaning the modules and typically restored production levels to 99.5% of a cleaned module.

Mejia, Kleissl and Bosch (2013) investigated the effects of soiling and accumulation of dust on the optical efficiency of a concentrated solar power system (CSP). The efficiency change was monitored in a large commercial site with 86.4kW at Santa Clara, California for a period of one year in 2010. The soiling losses in this study were found to result in a reduction in efficiency from 7.2% to 5.6% during 108 days of the dry period. During the rainy season, the efficiency increased to 7.1% owing to the washing by rain (Mejia, Kleissl, & Bosch, 2013).

Vivar et al., (2008) investigated the effects of soiling on flat plate (FP) and concentrated solar power system (CSP). The study found that FP system had a 4% reduction in power output due to dust while the CSP system experienced more light scattering preventing the focusing ability (Vivar, Herrero, Moreton, Martinez-Moreno, & Sala, 2008).

Ghosh (2014) investigated the effects of dust and shading by shadow on the electrical output of a flat plate (FP) system in India. The results indicate that the efficiency was reduced by 7%. When the temperature increased; the V_{oc} , fill factor and shunt resistance reduced. Dust was found to significantly alter the I-V characteristics of the solar panel (Ghosh, 2014).

Hafiz et al., (2014) carried out experiments to investigate the effect of dust deposited on the surface of two different types of photovoltaic modules (mono-crystalline silicon and polycrystalline silicon). The dust density deposited on the modules surface was 0.9867mg/cm^2 at the end of the study. The results showed that dust deposition has a strong impact on the performance of photovoltaic modules. The monocrystalline and polycrystalline modules showed about 20% and 16% decrease in average output power respectively as compared to clean modules of the same type (Hafiz, Zafar, & Nasir, 2014).

2.3 Literature Review Summary

Although extensive research has been carried out in most parts of the world, there is no information and data on the effects of soiling in Kenya specifically Nairobi.

Previous research indicated that effects of soiling are site specific and depends on the soil characteristics, topography as well as environmental factors such as wind speed and relative humidity. Most of the reviewed literature indicated that no research has been conducted in East Africa and in particular, Kenya.

An analysis of literature showed that soiling was affected by many parameters such as orientation, humidity, wind speed, soil characteristics, tilt angle, height, and type of PV. This research was therefore imperative as the local effects of these factors on solar PV characteristics in Kenya and East Africa have not been determined by any previous research. There are also few, if any research articles on the impact of the soiling on the performance of a solar pump.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Overview

The main aim of this project was to expose PV panels to the environment so that they were naturally soiled and the effects evaluated relative to a clean module. A quantitative analysis of the effect of soiling on solar photovoltaic systems and solar water pumping system was carried out. This entailed the setting up of an experiment to investigate these effects.

3.2 Study area

The experiments were carried out at two sites located in Nairobi. Nairobi City is Kenya's capital and is located within 1° 9' S, 1° 28' S and 36° 4'E, 37° 10'E, it covers an estimated area of 684 km^2. The city's altitude ranges from 1500 m to the east to approximately 1900 m to the west. It has a modified equatorial climate of the highlands characterized by a bimodal rainfall with a "long rain" season in March–May (MAM) and a "short rain" season in October–December. Nairobi is the most populous city in Kenya with a population of 5 million people. The activities within the city generate a lot of materials that accumulate on PV and cause significant performance degradation. The main effects of soiling in Nairobi include; paved roads, dust from nearby industries, cement from on-going construction works, soil erosion induced by wind gusts and vehicular pollution especially in the industrial area.

3.3 Materials and research instruments

The following equipment and instruments were used during research

- Solar PV panels – polycrystalline silicon solar PV panels rated 85 W were used in this study. A total of three modules generating were used. The specifications for the modules used in this study are tabulated in Table 3.1

Table 3.1: The specification of solar modules used

Module type	YL85P-17b
Manufacturer	Yingli solar
Solar module type	Polycrystalline
Dimensions (L×W×H)	901mm×606mm×24mm
Weight	6.65Kg
Maximum rated power	85.0 W
Rated voltage	18.1 V
Rated current	4.71
Maximum open circuit voltage	22.4 V
Maximum Short circuit current	4.99A
Maximum system voltage	50V
Module efficiency (manufacturer specified)	14.1%
Standard test conditions (STC)	Irradiance(1000W/m^2) Temperature25^{0}C SpectrumAM1.5g (EN 60904-3)
Possible applications	Solar power stations Rural electrification Small home power systems Power supply for traffic lights, security, gas industry 12V and 24V battery charging systems

- I-V curve tracer- This equipment was used to measure the short circuit current and open circuit voltage of the modules and plot the I-V curves.
- Multi-meter set: this system was configured to measure the current and voltage of the system. Four multi-meters were used to measure electrical parameters.
- Camera- was used to take photographs of the study site
- Flow meter- was used to measure the water pump flow rate.

3.4 System Installation

Two experiments were set up at two different locations in Nairobi Area. One was at the Davis & Shirtliff Industrial area and the other was set up in Karen where a solar pump has been installed with two modules. The first site was chosen due to its proximity to Nairobi and the boundaries of a highly polluted environment. The second site was selected to measure the actual effects of soiling on the solar pump. A comparative experimental study was conducted and data collected over a period of three months, February, March and April 2016.The setup was as shown in Figure 3.1.

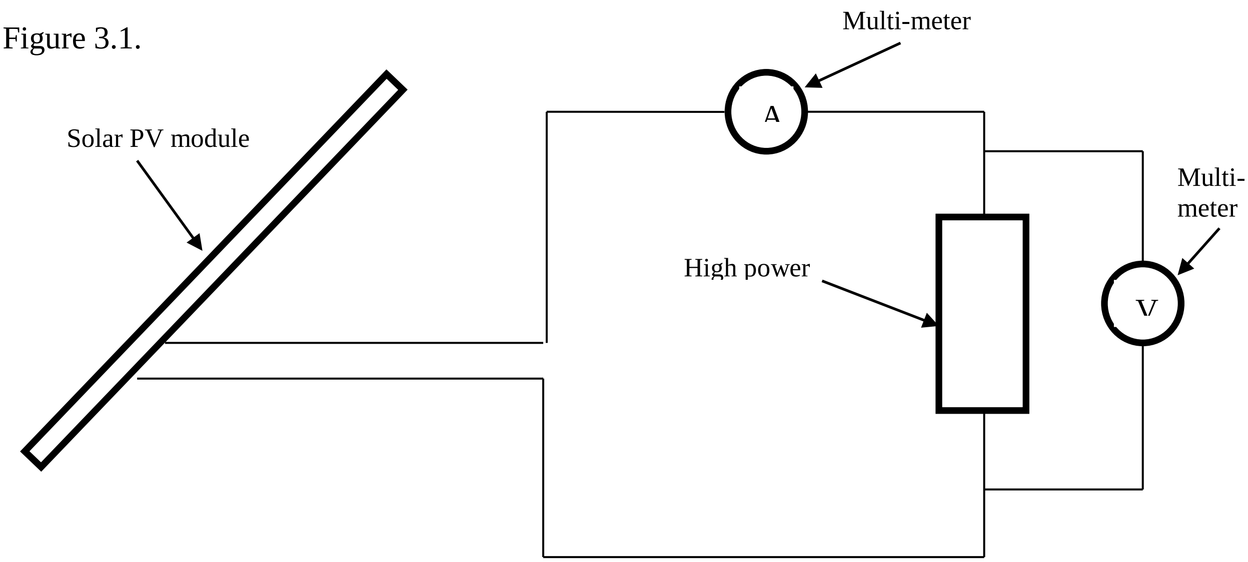

Figure 3.1: Experiment test and calibration circuit

3.5 Data Analysis

The data from the industrial area site was cross tabulated in tables indicating the tilt angle, cleaned or not cleaned, short circuit current, open circuit voltage and weather condition. The data from site Karen site was cross tabulated in tables indicating the week, the output voltage, current and pump flow rate.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 Solar irradiance for the study period

The irradiance data was collected three times each day for the whole study period. Figure 4.1 shows the recorded reading of irradiance in W/m^2 from1st Feb to 30th April.

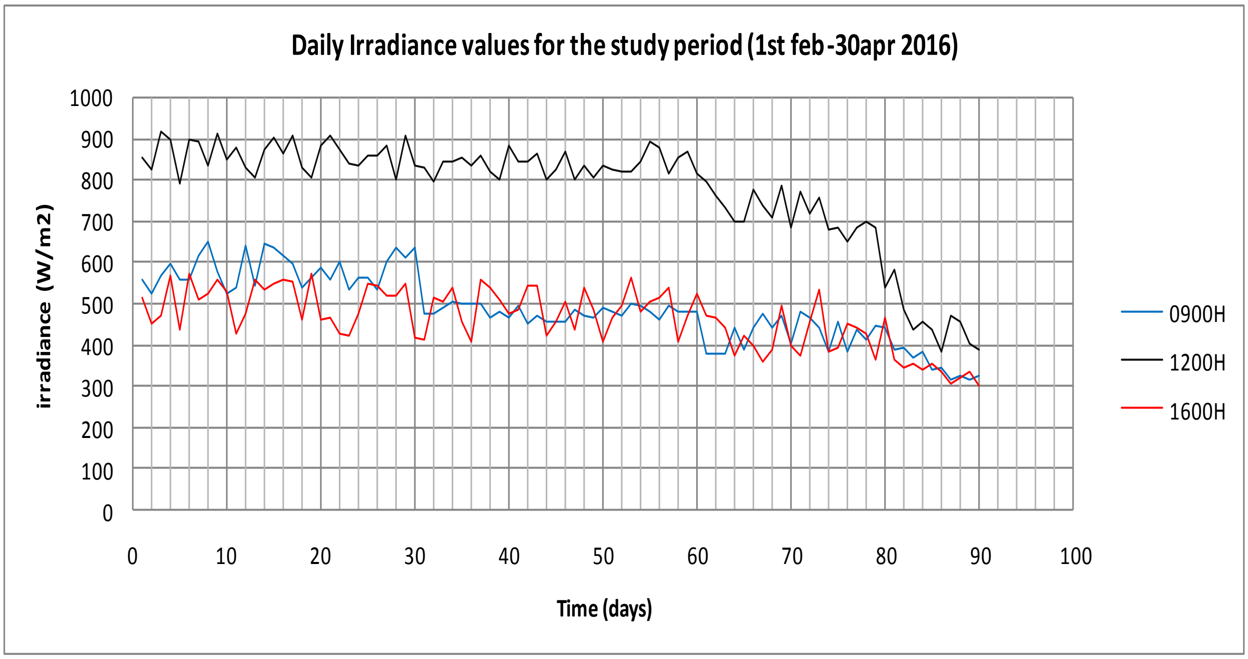

Figure 4.1: Recorded irradiance values for the study period

4.2 Average Power Output Variation due to Soiling

The performance of PV devices is characterized by a variation of current with voltage. V_{oc} is the voltage at the device terminal when the current is equal to zero. I_{sc} is the current at the device terminal when the voltage is equal to zero. The product of current and voltage values results in power of the module. Power output of the solar module is an important characteristic as it determines the actual power developed by the panel. The power variation over the study period for the different study panels is shown in Figure 4.2.

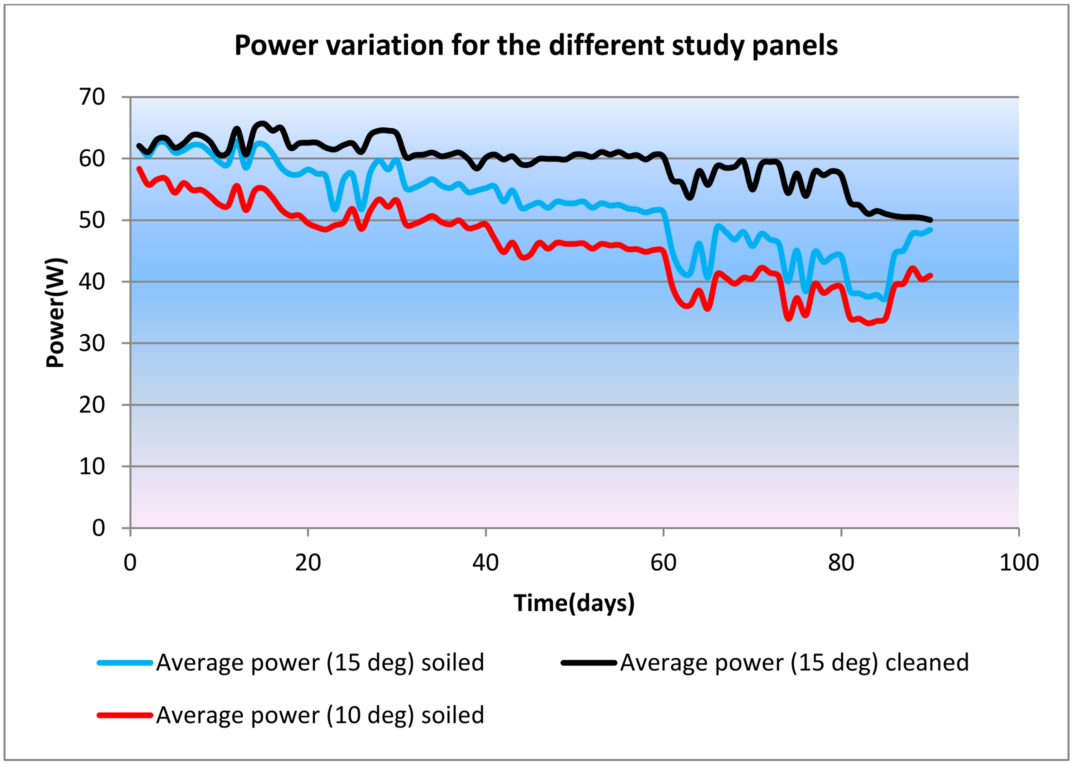

Figure 4.2: Daily power variation of the study PV panels

Figure 4.2 shows that soiling had a big impact on the power generated by the panel. The panel that was cleaned regularly had an output of 59.4W which was lower than the manufacturing rate of 85 W. For the month of February and March 2016, the cleaned module developed 60W. For the soiled panel installed at 15°tilt angle, the power was initially similar to that of cleaned module during the first few days. The value however decreased linearly over the study period due to accumulation of dust. The results indicated that there was a continuous decline in power developed by the panel over the 90 day study period. On average, the soiled module at 15° tilt angle had a power output of 52.2 W and this was equivalent to 12% drop in the power output.

The largest power decline was recorded from day 60 onwards with some days recording as low as 37.32 W for soiled module against 51 W for the regularly cleaned panel (26% drop in power output). Day 61 and 62 had small precipitation which made more dust to stick coupled with low irradiance level occasioned by the cloud cover. The reduction in power output can only be attributed to accumulation of soil as both the cleaned and soiled modules were kept in the same environmental conditions. The dust layer resulted in reduction of the incident light coming into the PV module and, in turn, reduced the power output of the module.

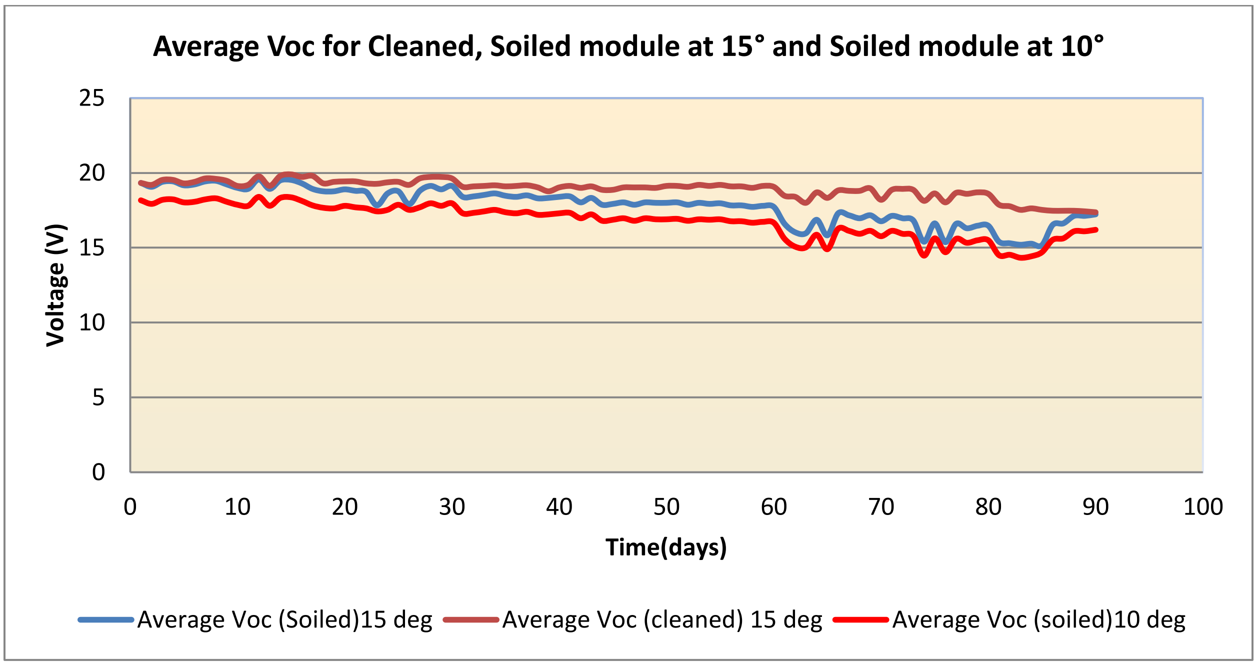

Figure 4.3: Average daily variation in Voc for study period

Tilt angle was also found to affect the power output considerably. Figure 4.3 shows that the output of the soiled panel at 15° had high power as compared to that mounted at 10°. This difference was only attributed to differences in soiling rates as all other factors were similar for the two modules. PV panel installed at higher tilt angle had an average power output of 52.22W while that mounted at 10° tilt angle had an average output of 46W. Therefore, the increase in tilt angle reduced soil accumulation and subsequently resulted to 11.9% increase in power.

4.3 Fill factor and I-V Characteristics

The performance of solar panels is generally demonstrated by variation of current over the voltage. This is known as the current voltage (I-V) curve. The Fill Factor in this study was investigated for both cleaned and soiled panels. The first tests were done to determine the I-V characteristics of the clean solar modules before data collection. The calibration tests are shown in Figure 4.4. These tests were done on sunny and cloudy days. It was observed that the results were significantly different due to increased power output on a sunny day as compared to the cloudy day.

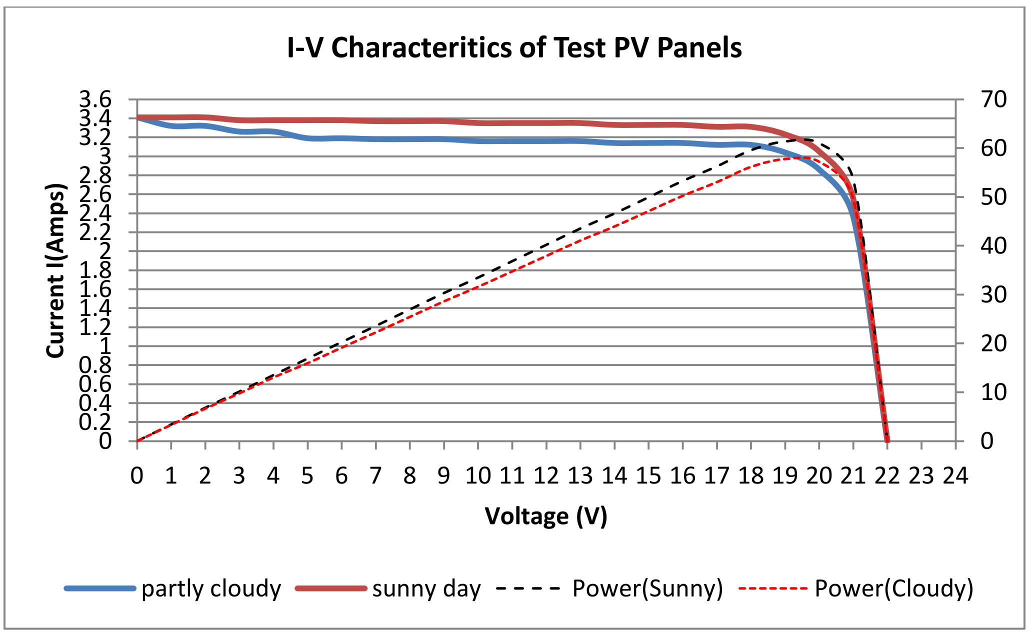

Figure 4.4: The I-V characteristics of the tests panels

The I-V characteristics on a sunny day were better as compared to those of a cloudy day. On a sunny day, the maximum current was 3 A. Figure 4.4 shows that the fill factor on a sunny day was higher as compared to that on a cloudy day. The maximum power point on a sunny day was observed to be $P_{mp} = 61.4$ W and this corresponds to a maximum current $I_{mp} = 3.23$ A and a maximum voltage$V_{mp} = 19$ V. Therefore, the fill factor can be determined graphically using the Equation (4.1)

$$\text{Fill Factor(FF)} = \frac{\text{area A}}{\text{area B}} = \frac{\text{area under } P_{mp}}{\text{area over } P_{mp}} = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \qquad (4.1)$$

Therefore, reading values from Figure 4.4, the FF on sunny day

$$\text{Fill Factor(FF)} = \frac{19 \times 3.23}{(22) \times (3.41)} = \frac{61.37}{75.02} = 0.81 \qquad (4.2)$$

The fill factor for the cleaned module on a sunny day was 0.81 or 81%. In an ideal case, the fill factor would be unity (=1). The none-rectangularity of the curve can be attributed to losses in irradiance, temperature effects and lower conversion efficiencies.

On a cloudy day, the maximum power point in Figure 4.4 was found to be 57.8W and this corresponds to a maximum current $I_{mp} = 3.04\ A$ and a maximum voltage $V_{mp} = 19$ V. The FF on a cloudy day was as shown in Equation (4.3)

$$\text{Fill Factor(FF)} = \frac{19 \times 3.04}{(22) \times (3.41)} = \frac{57.76}{75.02} = 0.77 \qquad (4.3)$$

Thus, the Fill Factor on a cloudy day was less than that observed on a sunny day. This can be attributed to loss in irradiance.

4.3.1 Effects of soiling on I-V Characteristics and the Fill Factor

I-V characteristics of the modules were investigated at the beginning of February (calibration tests) as well as at day 25 of every month. The results were used to plot the I-V curves and determine the FF.

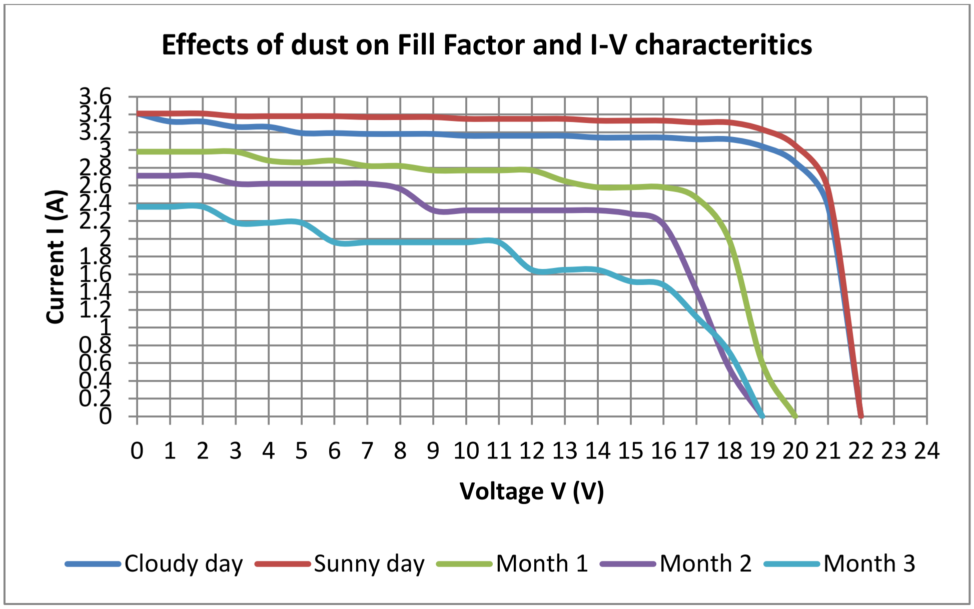

Figure 4.5: Effect of soiling on I-V characteristics and Fill Factor

Figure 4.5 shows that accumulated dust has a severe impact on I-V characteristics and the FF. In the first month, there was drastic reduction in output current to 3 A while the output voltage reduced to 20 V. The I-V characteristics show that the rectangularity of the I-V curve was distorted and the area reduced considerably. In the second month, the I-V curve was further distorted and there was increased loss in rectangularity. The output power reduced considerably over the entire three months period.

Figure 4.6 shows the effects of dust on FF, I-V characteristics as well as the power curves. The accumulation of dust caused a decrease in FF from 0.81 to 0.70 or a 13% reduction in FF during the first month. The reduction in FF also caused a significant decrease in power output. The cleaned module had a maximum power point of $P_{mp} = 61.4$ W while the soiled module had a $P_{mp} = 41.8$ W. This represents a power reduction of 31.9%.

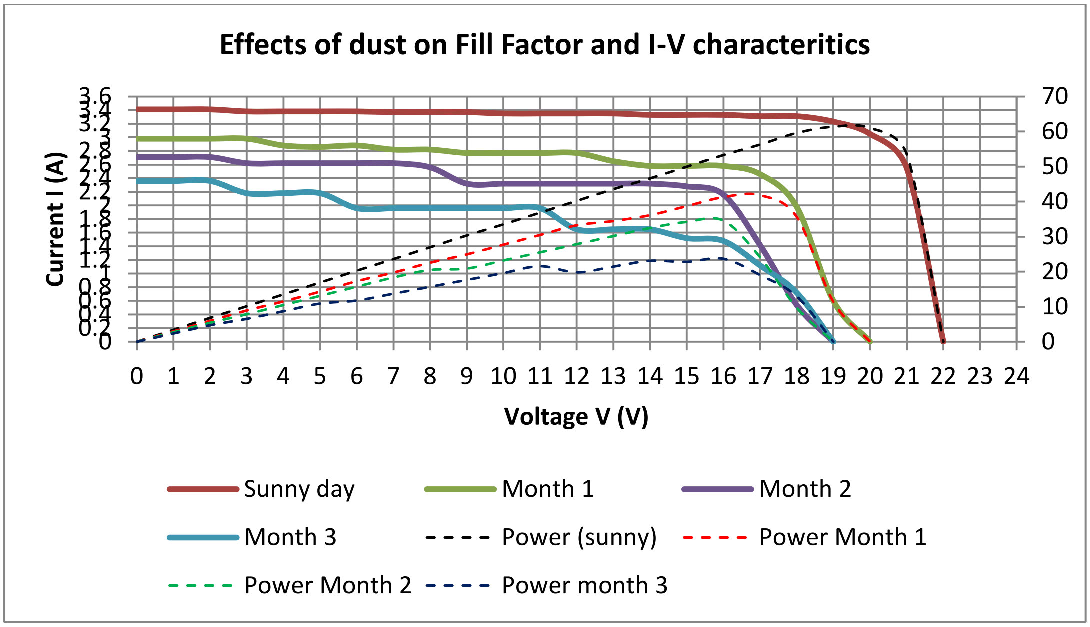

Figure 4.6: Effects of soiling on FF, Power and I-V over the study period

The summary results on variation in I_{mp} , V_{mp}, P_{mp} and FF due to soiling are tabulated in Table 4.1.

Table 4.1: Summarized results on effects of soiling on FF.

Parameter	Cleaned	Soiled (25 days)	Soiled (50 days)	Soiled (75days)
Maximum power point (P_{mp})	61.4W	41.8 W	34.5W	23.68W
Maximum voltage (V_{mp})	19V	17V	16V	16V
Maximum current (I_{mp})	3.23	2.64	2.16	1.48
FF	0.81	0.7	0.67	0.52

4.3.2 Effects of tilt on I-V Characteristics and the Fill Factor

The effects of tilt angle on I-V characteristics, FF and maximum power were investigated using the soiled panels. The readings were collected from the module mounted at 10° tilt angle at the same interval as those collected using the panel tilted at 15°. A summary of the effect of tilt angle on the Power, FF, voltage and current is shown in Table 4.2. It can be seen that there was a gradual loss in the power, voltage and current and these are attributed to soiling loses.

Table 4.2: Summary results on effect of Tilt angle

Parameter	Cleaned	Soiled (25 days)		Soiled (50 days)		Soiled (75days)	
		15°	10°	15°	10°	15°	10°
Maximum power point (P_{mp})	61.4W	41.8 W	36.48	34.5W	32.4	23.68W	24.3W
Maximum voltage (V_{mp})	19V	17V	16V	16V	15V	16V	15V
Maximum current (I_{mp})	3.23	2.64	2.28	2.16	2.16	1.48	1.62
FF	0.81	0.7	0.71	0.67	0.66	0.52	0.56

4.4 Effects of Soiling on Efficiency

The module efficiency depends upon the output power and solar irradiance and it degrades with the dust accumulation on the PV module surface. The module efficiency showed an inverse relationship with the solar irradiance and module temperature. At the beginning, the clean and soiled panels had almost equal conversion efficiency. The average irradiance was calculated from daily average irradiance levels at 9 am, 12 and 4 pm. This was found to be 574 W/m^2. The efficiency was computed using the values of FF, V_{oc} and I_{sc} as

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}} \text{ where } P_{in} \text{ the irradiance} \quad (4.4)$$

Efficiency of the cleaned module

$$\eta_{cleaned} = \frac{22 \times 3.41 \times 0.81}{574W/m^2} = 10.5\% \quad (4.5)$$

Table 4.3: Summary results on effects of Soiling on Efficiency.

Parameter	Cleaned	Soiled (25 days)		Soiled (50 days)		Soiled (75days)	
		15°	10°	15°	10°	15°	10°
Efficiency %	10.5	7.26	6.3	6.0	5.56	4.0	4.22

A comparative analysis of the efficiency is shown in Figure 4.7. The cleaned module had a conversion efficiency of 10.5 %. At the end of the first 25 days, the conversion efficiency of the soiled panel installed at 15° reduced to 7.26% while that mounted at 10° reduced to 6.3%. A lower tilt angle caused a slight reduction in efficiency due to increased dust accumulation.

At the end of day 50, the conversion efficiency of the soiled module installed at 15° was 6.0% as compared to 5.56% for the panel installed at 10°. At the end of 75 days, the efficiency dropped to 4.0% and 4.22% for module mounted at 15° and 10° tilt angle respectively.

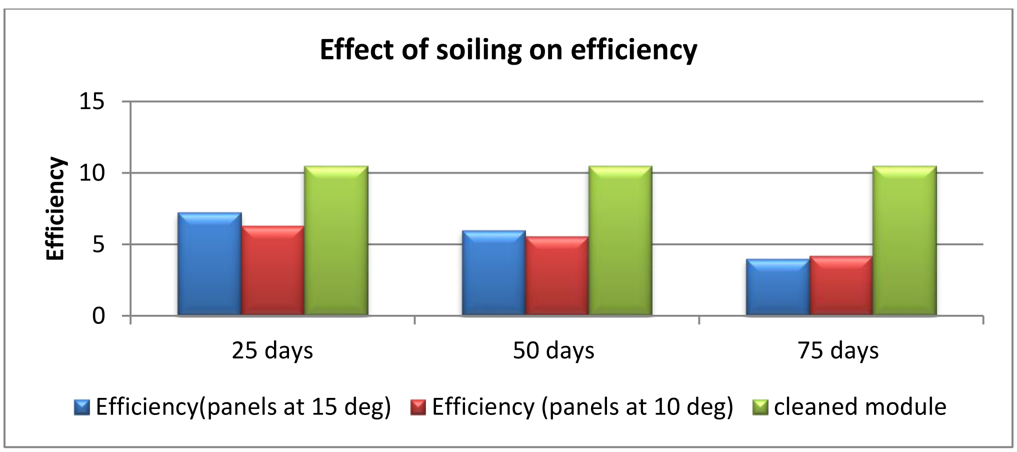

Figure 4.7: Effect of soiling on efficiency

4.5 Average Daily Soiling Loses

The average daily soiling losses were computed from daily power output of the cleaned module, the soiled module installed at 15° and that installed at 10°. The soiling loses were calculated as shown in Equation (4.6)

$$\% \text{ soiling losses} = \frac{(\text{Power}_{\text{cleaned module}} - \text{Power}_{\text{soiled module}})}{\text{Power}_{\text{cleaned module}}} \times 100\% \qquad (4.6)$$

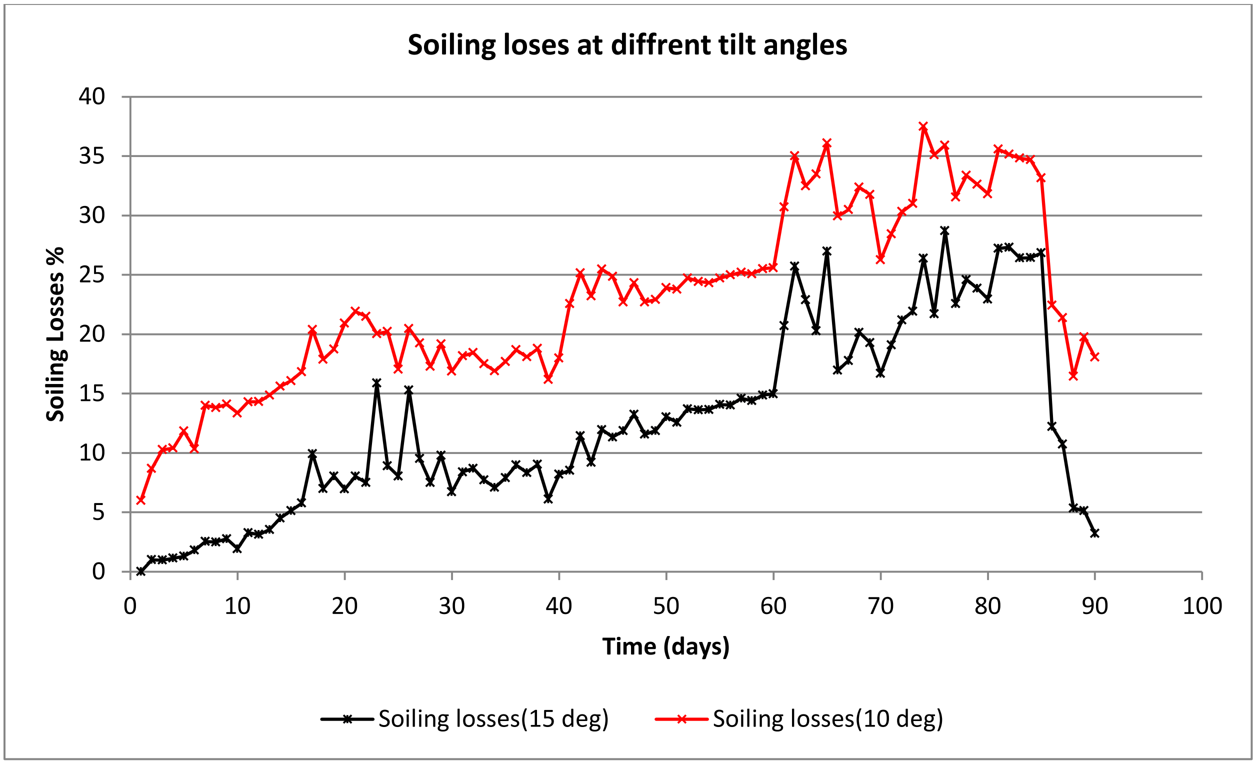

Figure 4.8: Soiling losses for the PV panels at different tilt angles

Figure 4.8 indicates that soiling losses had negative correlation with tilt angle. As the tilt angle decreased, the soiling losses increased. The average soiling losses increased over the 85 day period before the onset of rains in the last 5 days. The cumulative soiling losses indicate that soil accumulated over the panel and this increased the losses over time. For the panel mounted at 15°, the soiling losses increased from 0% to a maximum 15.88% on day 15. The average monthly soiling losses for the month of February were 9%. For March, the average soiling losses increased to 14%. This trend continued in the third month with drastic rise in soiling loses. The losses increased to a maximum of 29%. There was a sharp increase and decrease in losses due to heavy accumulation in dust, reduction in irradiance due to increased cloud cover in April and the effect of dew and drizzling which caused dust to stick rather than washing the module. The module installed at 10° tilt angle also showed the same trend but had higher soiling loses.

4.5.1 Effects of Soiling Losses on Flow Rate

A comparative analysis of the effects of flow rate for cleaned and soiled panel was done. The cleaned module tests were done on the first day after the module was cleaned. The weekly changes in flow rate were recorded at a head of 20 meters. The results are shown in 4.9.

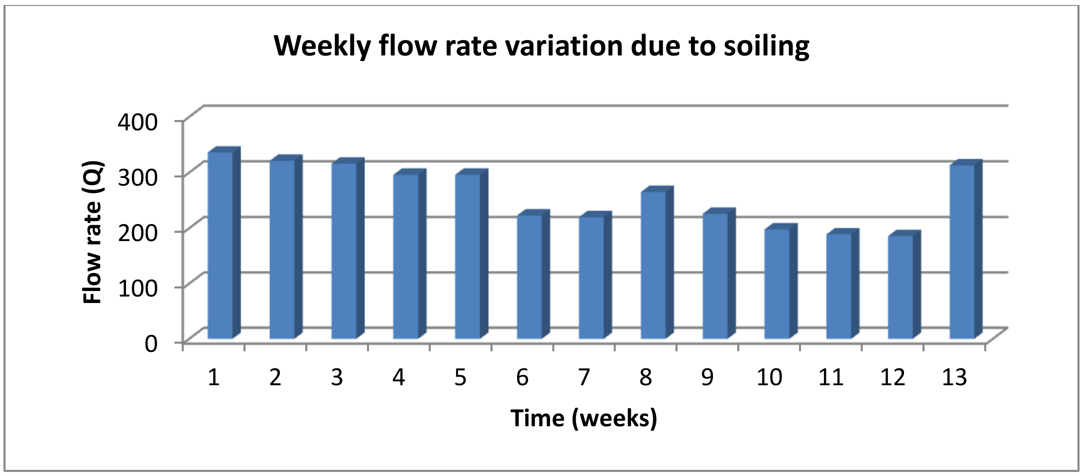

Figure 4.9: The weekly variation in Flow rate due to soiling

Figure 4.9 indicates that soiling had an impact of the pump flow rate. In the first week, the clean module had a flow rate of 336 LPH at a head of 20m. This reduced in the subsequent weeks as dust accumulated on the surface of the module. In the second week, the flow rate reduced to 321LPH. This tread continued up to week 7 with the flow rate dropping by 34.5 %. It was noticed that the effects of wind and small amount of rain cleaned the module in week 8 causing a slight increase in the power generated by the module and subsequently, an increase in flow rate. The rain and wind effects were found to cause deposition and also removal of particles from the panel. Low wind speed and drizzling increased the soiling effects while strong winds dislodged some particles increasing the flow rate. The effects of rain and wind did not significantly clean the module and therefore soiling continued. The downward trend was observed through week 9, 10, 11 and 12. In the last week, the observed tread changed due to the onset of rains that cleaned the soiled panel and increased the flow rate.

4.5.2 Effects of Soiling Losses on Flow Rate at Different Delivery Head

The flow rate of the pump was monitored using a flow meter installed at the delivery head of the pump.

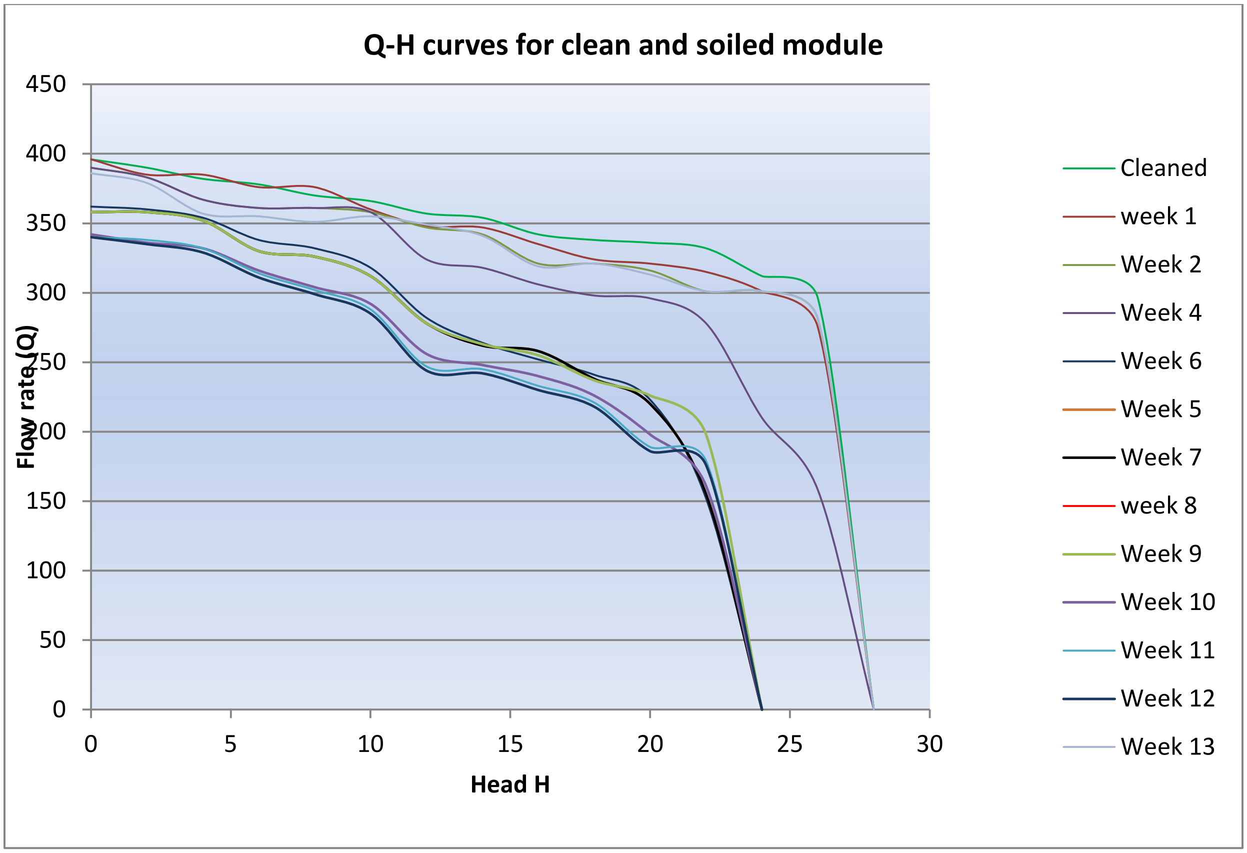

Figure 4.10: Variation in Q-H curves due to soiling

Figure 4.10 indicates that there was large variation in the Q-H curves due to soiling. The cleaned module had a high power output and was found to deliver 396 LPH at no head and 296 LPH at 26 m. It was observed that the pump had low flow rate variations at heads between 0 to 25 m but the flow rate sharply declined to zero at higher heads. During the first four weeks, there was a slight reduction in the power and this had a weak effect on the performance curves. It was noted that soiling affected the pump more at higher heads as compared to low head. This can be attributed to the fact that as the head increased, the hydraulic resistance increased causing more opposition to the water flow. As time progressed, more and more dirt settled on the panel increasing the drop in flow rate.

4.5.3 Effects of soiling power output

Open circuit voltage is one of the critical performance characteristics of PV panels. In this study, the average variation in voltage between clean and soiled module was 6.4 % while that of the current changed by 7%. The accumulation of dust and grime on the panel causes increased reduction in V_{oc} and I_{sc} unless action is taken to clean the panel. Previous studies also document a reduction in voltage and current but the figures obtained in this research were significantly different owing to the fact that dust accumulation is affected by the properties of the surrounding environment (Hussein, Tamer, Sopian, Buttinger, Elmenreich, & Ahmed, 2013). The power output of PV panels is directly related to the current and voltage, therefore any change in V_{oc}, and I_{sc} causes a proportionate reduction in the power output. In this study, the power output decreased by 12.2% due to accumulation of soil on the surface of the soiled panel as compared to the clean module.

4.5.4 Impacts of soiling on efficiency

The efficiency of a PV-solar cell is determined by the amount of electrical power generated, to the incoming solar power available at the surface. The efficiency of the solar module is determined by the electrical power output to light energy input. The power output is affected by the fill factor and therefore, the maximum power is adjusted by the FF. Previous studies document that most solar panels have an efficiency that ranges between 15-25%. The efficiency depends on the type of technology used to construct the cells. Mono- crystalline, polycrystalline, amorphous and thin films all have varying efficiencies. Tests yielding high efficiencies are only possible at standard test conditions (STC). Incoming radiation at the Earth's surface varies considerably from the STC and therefore, most panels will have efficiencies ranging between 10 – 15%.

In this study, it was found that the soiling affected the efficiency of the modules. For the cleaned module η was 10.5% while the soiled module had an efficiency of 7.26% for the first 25 days and this dropped to 4% after 75 days. Thus, soiling was associated with shading of the cells and resulted in loss of irradiance due to absorbance, scattering, obstruction and reflection of the incident light. Soil accumulation on the glass surface alters the reflectance, transmittance and absorbance properties of the PV panel and this has significant degradation on the efficiency.

4.5.5 Effects of soiling on fill factor and I-V curves

The fill factor and I-V curves are important performance characteristics in any PV panel. FF represents the rectangularity of the I-V curves. In this study, soiling was found to cause significant reduction in FF. The cleaned module had an FF of 0.81 while the soiled module had FF of 0.7 in the first 25 days. The FF was also found to increase with time as more dust accumulated on the surface of the module. After 50 days, FF for the soiled module had reduced to 0.67. This value further reduced to 0.52% after 75 days. The reduction in FF can be attributed to reduced incident light due to changes in glass properties which subsequently altered reflectance, transmittance, absorbance and refractive index.

4.5.6 Effects of module installation on soiling

Most PV systems have specific set up specifications. This study investigated if the specified angle of tilt has any impacts on the performance factors of the solar panel. The results showed significant differences between the soiled module installed at 15° and that mounted at 10°. In terms of average V_{oc}; the soiled module at 10° TA had 5.8% less open circuit voltage as compared to the panel at 15° TA. In terms of I_{sc} , the module at low TA had 6.5% less current as compared to the panel mounted at higher TA. The same trend was observed for the power output (11.9% reduction in power output). TA also slightly affected the FF of the modules. Increase in tilt angle reduced the efficiency of the PV system. For example the soiled module at 15° had an efficiency of 7.26% in the first month while that mounted at 10° had an efficiency of 6.3%. These results were similar to previous studies which show variations in soiling due to changes in tilt angle (Garcia, Marroyo, Lorenzo, & Perez, 2011).

The increased dust accumulation due to reduction in tilt angle can be attributed to gravitational forces and dust adherence mechanisms. Large tilt angles cause less soil to attach due to gravitational forces, and will therefore result in a reduced soil density on the module surface as observed with the panel installed at 15° TA. When the TA increases, dust particles are easily rolled away from the surface by a combination of wind and gravitational pull. When considering gravity, horizontal surface accumulate more dust as compared to vertical ones. This effect is combined with wind speed. Low wind speed wind pattern promotes dust settlement while high wind speeds dislodge dust from the surface.

4.6 Effects of environmental and climate factors on soiling rate

Environmental factors play an imperative role in the initial adhesion, dust accumulation and dust removal from the surface**.** The dust deposition mechanism depends on five main factors which are normally affected by environmental and weather patterns. These are (i) dust transportation, (ii) initial adhesion, (iii) change in adhesion mechanisms, (iv) alterations in the surface properties and dislodging/ self cleaning mechanisms. The process of transporting dust to the surface of a PV module is mainly due to wind which uptakes soil particles and moves them to another location. The uptake of particles is affected by ground conditions such as wetness, speed, particles size and soil texture. High wind speed causes rapid uptake of particles. In this study, it was observed that the industrial area site had more dust accumulation owing to environmental conditions that promoted high particle uptake and transportation to module. In addition, small particles from dust and soil can remain in the atmosphere for long periods of time before being transported and finally settling on the module.

4.7 Effects of location on soiling rate

Local variations or site specific conditions have a large impact on the level of dust accumulation. In this study, it was found that the industrial area site recorded high soiling rates as compared to the Karen site. Increased soiling losses caused significant differences between the two sites in terms of the power, V_{oc}, I_{sc}, FF, efficiency and soiling loses even though similar solar panels were used and the same irradiation levels recorded in the two sites. This difference can be explained in terms of site specific conditions that cause variations in soiling losses. Location factors can be classified as physical and human characterizations. The physical factors are natural and include factors such as weather, soil type, soil composition, vegetation cover, and topography. Human factors on the other hand include factors caused by human activities such as pollution, industrial activities and agriculture.

The main soiling agents include dust, soil, sand, cement, smoke from factories, households and cars, minerals, chemicals, clay and silt. These agents range from coarse to very fine particles. Each type of these particles has a rate at which they will fall on any given surface. The small particles which form thin smoke and haze are suspended in the atmosphere and do not fall. As the particle size increases, the rate of fall of these particles increases and this increases soiling. Fine particles are also easily transported and adhere strongly on the module as compared to coarse particles.

Vegetation cover can act as a hindrance to high wind speed and this reduces the soil transportation and subsequently reduces the soiling rate. Human factors such as pollution from factories, vehicle smoke, etc. cause significant dust accumulation as seen in the industrial are site which was close to pollution from vehicles, industries, dust and other pollutants.

4.8 Solar Water Pump Performance

In this study, it was found that the amount of water pumped was affected by dust accumulation on the PV module. Increased dust accumulation affected the output power of the solar module which in turn affected the performance of the pump. The panel characteristics such as V_{oc}, I_{sc}, maximum power, efficiency and FF were affected by dust and increased soiling rates and these subsequently affected the performance of the pump.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

This study investigated the effects of soiling on the performance of solar Panels as well as the impact of soiling on the solar water pump system performance. This project was set up at two sites in Nairobi: Karen and industrial area. The impact of cumulative accumulation of dust and other airborne particles was investigated by collecting data from solar panels exposed to sunlight in conditions that mimic their real life application. Data was collected from the months of February to April 2016. The performance of the solar panels were evaluated using the testing parameters that included open circuit voltage, short circuit current, average daily power output, fill factor, I-V characteristics and the soiling losses. The performance of the solar water pumping systems was evaluated using imperative performance metrics such as flow rate, head and Q-H characteristics. It can be concluded that:

- The performance of the solar PV panel was affected by daily irradiance, cloud cover and temperature values over the entire study period. The difference between the clean and soiled module was the only way to quantify the effects of dust as the panels were kept in similar environmental conditions.

- Dust adhesion on a solar PV depends on the properties of panel surface and dust particle, its composition, chemistry, degree of smoothness or roughness, electrical properties (conductivity and charge), orientation, tilt angle, environmental factors, weather, soiling, location, optical properties, temperature and mechanical motion.
- Dust had a significant impact on the average daily power generated by the panel, I-V characteristics, and FF.
- The pump performance in terms of flow rate, head and Q-H curves were significantly lowered by accumulation of dust. As dust levels increased, the pump performance reduced. The performance of the pump at high head was seriously affected by dust as compared to its performance at lower heads.

5.2 Recommendations

This project demonstrated the effects of soiling on the performance of PV modules as well as the impact of dust on solar water pump performance. The effects of dust on various parameters were determined. From the results obtained, the following recommendations were made

- Since solar PV systems already have low conversion efficiencies of 10 – 25%, it is imperative for more site specific studies to be carried out to fully understand the effects of soiling on the performance of PV panels as further decrease in the performance will decrease the system efficiency and make them an unattractive source of energy.

- The results obtained are suitable in determining a correction factor to be introduced during design and system sizing to cater for the power loses associated with soiling. From the study, a correction factor of 12% would be the optimum one.
- It is imperative to clean solar panels on a weekly basis to avoid soiling losses. This can be done manually or the modules should incorporate an automatic solar panel cleaning mechanism by the use of sprinkler system.
- Further work needs to be done to determine soiling effects over longer periods of time, effects due to specific dust particles as well as impact of other site specific factors in different localities in Kenya.

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APPENDIX

Appendix A: Raw data for Voc and Isc at 9.00am

Day	Irradiance	Voc (Soiled)	Voc (cleaned)	Isc (soiled)	Isc (cleaned)
1	516	18	18	3.03	3.03
2	453	17.6	17.8	2.96	2.99
3	474	18	18.1	3.03	3.04
4	567	18.1	18.2	3.04	3.06
5	440	17.8	17.9	2.99	3.01
6	574	17.9	18.2	3.01	3.06
7	510	18.1	18.4	3.04	3.09
8	527	18.2	18.4	3.06	3.09
9	561	17.9	18.1	3.01	3.04
10	529	17.6	17.8	2.96	2.99
11	426	17.3	17.6	2.91	2.96
12	477	18.3	18.6	3.08	3.13
13	560	17.7	17.8	2.97	2.99
14	535	18.3	18.7	3.08	3.14
15	550	18.3	18.7	3.08	3.14
16	559	18.1	18.6	3.04	3.13
17	556	17.5	18.6	2.94	3.13

18	464	17.2	17.9	2.89	3.01
19	572	17.45	18.2	2.93	3.06
20	463	17.3	18	2.91	3.03
21	469	17.2	18	2.89	3.03
22	427	17.1	17.8	2.87	2.99
23	424	15.8	17.8	2.66	2.99
24	478	17.1	18	2.87	3.03
25	551	17.4	18.2	2.92	3.06
26	543	16.1	17.9	2.71	3.01
27	519	17.3	18.4	2.91	3.09
28	521	18	18.6	3.03	3.13
29	549	17.5	18.5	2.94	3.11
30	418	17.7	18.3	2.97	3.08
31	414	16.8	17.6	2.82	2.96
32	516	17.1	17.9	2.87	3.01
33	504	17.1	17.8	2.87	2.99
34	540	17.3	17.9	2.91	3.01
35	455	17	17.7	2.86	2.97
36	407	16.9	17.7	2.84	2.97
37	558	17.1	17.9	2.87	3.01
38	538	16.9	17.7	2.84	2.97
39	510	17	17.7	2.86	2.97
40	478	16.9	17.6	2.84	2.96
41	488	17	17.8	2.86	2.99
42	547	16.5	17.7	2.77	2.97
43	546	17	17.8	2.86	2.99
44	424	16.3	17.5	2.74	2.94
45	458	16.4	17.6	2.76	2.96
46	507	16.5	17.7	2.77	2.97
47	438	16.3	17.7	2.74	2.97
48	540	16.6	17.8	2.79	2.99
49	486	16.6	17.8	2.79	2.99
50	410	16.5	17.7	2.77	2.97
51	465	16.7	17.8	2.81	2.99
52	495	16.5	17.8	2.77	2.99
53	565	16.7	18	2.81	3.03
54	483	16.5	17.8	2.77	2.99
55	507	16.5	17.9	2.77	3.01
56	514	16.4	17.8	2.76	2.99
57	540	16.5	17.9	2.77	3.01
58	408	16.1	17.6	2.71	2.96

59	470	16.3	17.8	2.74	2.99
60	526	16.4	17.9	2.76	3.01
61	470	14.8	17	2.49	2.86
62	466	14.2	17	2.39	2.86
63	445	14.1	16.4	2.37	2.76
64	377	15.6	17.4	2.62	2.92
65	423	14.1	16.9	2.37	2.84
66	399	16	17.5	2.69	2.94
67	359	16	17.4	2.69	2.92
68	390	15.9	17.5	2.67	2.94
69	497	16.1	17.7	2.71	2.97
70	397	15.7	17.2	2.64	2.89
71	377	15.8	17.5	2.66	2.94
72	455	16	17.7	2.69	2.97
73	536	15.9	17.8	2.67	2.99
74	383	13.8	16.8	2.32	2.82
75	396	15.6	17.5	2.62	2.94
76	453	13.9	16.8	2.34	2.82
77	441	15.6	17.6	2.62	2.96
78	427	15.2	17.5	2.55	2.94
79	363	15.4	17.6	2.59	2.96
80	467	15.6	17.8	2.62	2.99
81	364	13.9	16.7	2.34	2.81
82	345	13.9	16.7	2.34	2.81
83	356	13.9	16.7	2.34	2.81
84	342	13.9	16.7	2.34	2.81
85	357	13.9	16.6	2.34	2.79
86	336	15.4	16.6	2.59	2.79
87	309	15.5	16.4	2.61	2.76
88	322	15.9	16.4	2.67	2.76
89	337	16	16.5	2.69	2.77
90	302	16.1	16.3	2.71	2.74

Appendix B: Raw data for Voc and Isc at 12.00pm

Day	Irradiance	Voc (Soiled)	Voc (cleaned)	Isc (soiled)	Isc (cleaned)
1	855	20.9	20.9	3.38	3.38
2	825	20.8	20.8	3.35	3.36
3	917	21	21.2	3.41	3.42
4	896	21	21.1	3.41	3.41
5	793	20.6	20.8	3.36	3.36
6	898	20.9	20.8	3.35	3.36
7	895	20.9	20.9	3.37	3.38
8	833	20.8	20.8	3.35	3.36
9	913	20.9	21.2	3.39	3.42
10	848	20.8	20.8	3.35	3.36
11	880	20.9	21.1	3.4	3.41
12	832	20.8	20.8	3.35	3.36
13	808	20.4	20.8	3.24	3.36
14	873	20.7	20.8	3.28	3.36
15	903	20.8	21.1	3.3	3.41
16	865	20.6	20.9	3.27	3.38
17	905	20.7	21.1	3.28	3.41
18	832	20.7	20.9	3.28	3.38
19	806	20.4	20.8	3.24	3.36

20	883	20.8	21	3.3	3.39
21	909	20.8	21.1	3.3	3.41
22	873	20.6	20.9	3.27	3.38
23	841	20.6	20.9	3.27	3.38
24	833	20.5	20.9	3.25	3.38
25	857	20.5	20.8	3.25	3.36
26	859	20.5	20.8	3.25	3.36
27	885	20.6	20.9	3.27	3.38
28	800	20.2	20.8	3.2	3.36
29	909	20.6	21.1	3.27	3.41
30	836	20.5	20.8	3.25	3.36
31	830	20.4	20.8	3.24	3.36
32	797	20.2	20.6	3.2	3.33
33	843	20.4	20.8	3.24	3.36
34	843	20.4	20.8	3.24	3.36
35	855	20.3	20.8	3.22	3.36
36	833	20.2	20.8	3.2	3.36
37	861	20.4	20.8	3.24	3.36
38	819	20.2	20.8	3.2	3.36
39	799	20.1	20	3.19	3.23
40	882	20.4	20.9	3.24	3.38
41	844	20.3	20.8	3.22	3.36
42	844	20.3	20.8	3.22	3.36
43	863	20.1	20.8	3.19	3.36
44	799	19.9	20.5	3.15	3.31
45	825	20	20.4	3.17	3.3
46	870	20.2	20.8	3.2	3.36
47	802	19.9	20.6	3.15	3.33
48	835	20	20.6	3.17	3.33
49	806	19.8	20.4	3.14	3.3
50	833	19.8	20.8	3.14	3.36
51	823	19.7	20.8	3.12	3.36
52	821	19.7	20.7	3.12	3.34
53	819	19.7	20.7	3.12	3.34
54	846	19.8	20.8	3.14	3.36
55	892	20	20.9	3.17	3.38
56	878	19.8	20.8	3.14	3.36
57	816	19.6	20.6	3.11	3.33
58	852	19.8	20.6	3.14	3.33
59	871	19.8	20.8	3.14	3.36
60	816	19.5	20.5	3.09	3.31

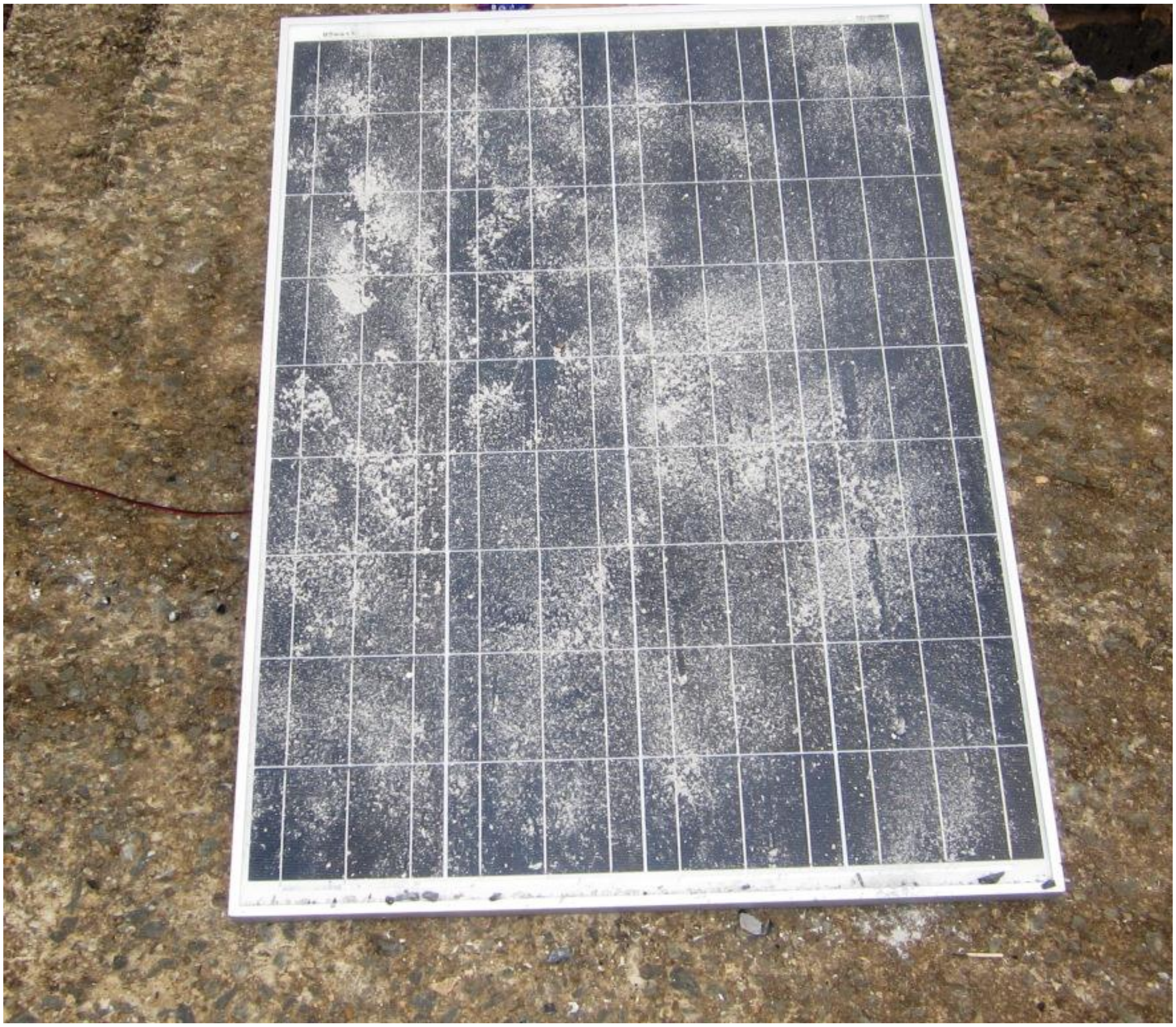
61	797	19.4	20.6	3.07	3.33
62	763	18.9	20.4	2.99	3.3
63	734	18.8	20.3	2.98	3.28
64	698	18.2	20.1	2.88	3.25
65	700	18.4	20.3	2.91	3.28
66	779	18.8	20.4	2.98	3.3
67	737	18.2	20.3	2.88	3.28
68	707	18	20.3	2.85	3.28
69	784	18.3	20.5	2.9	3.31
70	686	17.9	19.2	2.83	3.1
71	774	18.5	20.3	2.93	3.28
72	717	17.9	20.4	2.83	3.3
73	757	17.9	20.2	2.83	3.26
74	681	17.6	19.8	2.78	3.2
75	683	17.6	19.8	2.78	3.2
76	652	17.4	19.6	2.75	3.17
77	685	17.6	19.8	2.78	3.2
78	699	17.5	19.8	2.77	3.2
79	685	17.4	19.7	2.75	3.18
80	541	17.2	19.2	2.72	3.1
81	585	17.3	19.1	2.73	3.09
82	486	17	18.8	2.69	3.04
83	437	16.8	18.2	2.65	2.94
84	457	16.9	18.4	2.67	2.97
85	436	16.7	18.4	2.64	2.97
86	385	17.8	18.2	2.82	2.94
87	471	17.9	18.6	2.83	3
88	458	18.6	18.6	2.94	3
89	403	18.5	18.4	2.93	2.97
90	389	18.4	18.4	2.91	2.97

Appendix C: Weekly Voc raw data for soiled and cleaned panel at various tilt angles

WEEKS	Voc (soiled 0900Hrs) 15Deg	Voc (soiled 0900Hrs) 10Deg	Voc (soiled 1200Hrs) 15Deg	Voc (soiled 1200Hrs) 10Deg	Voc (soiled 1600Hrs) 15Deg	Voc (soiled 1600Hrs)10Deg
1.0000	19.0857	17.9429	20.8714	19.6000	17.9286	16.8286
2.0000	19.0429	17.9000	20.7571	19.5286	17.9000	16.8143
3.0000	18.7357	17.6000	20.6857	19.4857	17.5786	16.5429
4.0000	18.1571	17.0714	20.5000	19.3000	16.9714	15.9714
5.0000	18.3143	17.2000	20.4000	19.2000	17.2143	16.2000
6.0000	17.8571	16.7714	20.2714	19.0714	16.9000	15.9000
7.0000	17.5143	16.4857	19.9857	18.7857	16.5286	15.5286
8.0000	17.5143	16.4714	19.7857	18.5857	16.5429	15.5429
9.0000	16.4143	15.4571	19.4000	18.2286	15.4857	14.5429
10.0000	16.7143	15.7286	18.2571	17.1571	15.6286	14.6857
11.0000	16.2429	15.2714	17.7857	16.7000	15.2286	14.3286
12.0000	15.6143	14.6714	17.1571	16.1571	14.5429	13.7000
13.0000	16.4667	15.4833	17.9833	16.9000	15.4667	14.5333

Appendix D: Cleaned and soiled module

Soiled module at 15^0



Soiled module

Appendix E: Pump Systems Photographs

Solar water pumping system with flow meter and controller

Pump controller parts

Pump controller

Pressure gauge installed on the water pumping system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