OPTIMAL CLEANING STRATEGY FOR LARGE SCALE SOLAR PHOTOVOLTAIC ARRAY CONSIDERING NON-UNIFORM DUST DEPOSITION

by

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SUMMARY

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The use of solar photovoltaic systems has increased in the past years in an effort to move towards cleaner energy sources. Solar panels are however affected by negative factors such as dust deposition which hinder their performance. The negative effects that dust deposition has on solar panels depend on how much dust gets deposited on solar panels and how it spreads on the top surface. The spread of dust on solar panels can be uniform where all the solar panels in a entire solar photovoltaic array have the same amount of dust deposition. This is an ideal case and can be defined as uniform dust deposition. However, in real life operation, the spread of dust deposition can vary with one solar panel having a different quantity of dust deposition from another. This is defined as non-uniform dust deposition. Non-uniform dust deposition negatively affects the performance of solar panels by reducing the irradiance that reaches the solar cells thereby reducing the performance of the solar panels. The negative effects of non-uniform dust deposition are more significant over time and when there is no intervention to remove the dust.

In practice, the negative effects of non-uniform dust deposition on photovoltaic modules has been addressed by periodically cleaning their top surfaces. Periodic cleaning can however increase the operational costs in terms of the cleaning frequency, time taken, cost of cleaning resources and effectiveness. In this study, we propose an optimal cleaning strategy for the solar power plants that are

prone to the non-uniform dust deposition. To develop the optimal cleaning strategy, we first investigate the dust deposition process and develop a model to describe the relationship between the solar power generation and non-uniform dust deposition patterns. Then we formulate an optimization model to identify the most cost-effective solar panel cleaning plan. In the optimisation, the additional revenue due to cleaning the solar panels is formulated as the objective function. The decision variables are the number of photovoltaic strings cleaned at each cleaning interval. To highlight the effectiveness of the proposed solar panels cleaning strategy, the developed cleaning strategy is applied to a case study where analysis of the performances of other solar panel cleaning strategies, namely "full cleaning", "no cleaning" and "random cleaning" is done. The results from the study show that the optimal cleaning strategy outperforms all the other cleaning strategies showing its effectiveness.

The optimal cleaning strategy developed is useful to solar photovoltaic plants owners whose plants are located in dusty or polluted areas. It first provides them with an understanding of non-uniform dust deposition. It also provides a way of reducing the effects of non-uniform dust deposition through optimized cleaning which is cost effective and that allows the photovoltaic array to continuously give the desired output.

LIST OF ABBREVIATIONS

a-Si	Armophous silicon
c-Si	Crystalline silicon
CdTe	Cadmium telluride
CFD	Computational fluid dynamics
CIGS	Copper indium gallium selenide
DDM	Double diode model
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
EDS	Electrodynamic screens
FF	Fill factor
GHI	Global horizontal irradiance
GMPP	Global maximum power point
GTI	Global tilted irradiance
GW_{dc}	Gigawatts direct current
I-V	Current voltage graph
LID	Light induced degradation
LMPP	Local maximum power point
MABE	Mean absolute bias Error
MPP	Maximum power point
PR	Performance ratio
PV	Photovoltaic
P-V	Power voltage
RMSE	Root mean squared error
SDM	Single diode model
SHIP	Super-hydrophilic
SHOP	super-hydrophobic
SSDM	Simplified single diode model
STC	Standard test conditions
TF	Thin film
UV	Ultraviolet

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Installations of solar photovoltaic (PV) systems have increased in many countries because the technology is clean and renewable. Globally, at least 75 GW_{dc} of solar PV was installed in 2016 [1] and 98 GW_{dc} installed in 2017 [2], showing a 30.67% increase in installations. With increased installation, sustainability of their performance becomes important.

1.1.1 Dust deposition

The performance of solar panels is negatively influenced by factors such as dust deposition. Dust deposition for solar panels refers to settlement of dust on their top surfaces. The dust deposited can reduce the solar irradiance reaching the solar panel hence reducing its performance. The extent to which dust deposition affects solar panels depends on factors such as the size of dust particles, exposure period, tilt angle of solar panels, environment and weather conditions. The size of dust particles refers to how coarse or fine they are. Finer scale dust particles such as carbon cause more severe dust depositions and more power losses as they cover more surface area [3]. Larger dust particles such as sand occupy less surface area as compared to fine dust particles. Their effect on performance is therefore less. The exposure period varies from short to long. Longer exposure periods cause more power losses because dust continues to accumulate on the solar panels. Solar panels in Saudi Arabia exposed outdoors for 3 months [4] showed a 24.6% reduction in the power output. The same solar panels showed a reduction of 45.9% after 8 months of exposure.

The tilt angle of solar panels also influences the dust deposition process. Larger tilt angles allow for dust deposited to slide off the surface of solar panels while smaller tilt angles have all or most of the dust remain on the surface after deposition. The observation was made in a study in Egypt where transmittance loss of 21% was observed for solar panels tilted at 20° and 11% at 60° tilt angle [5]. Weather conditions such as rainfall and wind also influence the dust deposition process. Rainfall can wash away dust from solar panels when it falls plentifully and frequently thereby reducing the effects of dust deposition. Light rainfall in a dusty environment will however cause mud formation on the dusty solar panel leading to more loss in the transmittance. Solar panels in Kuwait [6] showed an increased loss of 25% in the daily yield after rain fell, due to the formation of mud when rainfall mixed with dust. Wind influences dust settlement and removal. Low wind speed promotes dust deposition as compared to high wind speeds. In dusty areas, strong winds carrying dust can cause scratches on the surface of solar panels [7]. Dust storms cause rapid dust deposition resulting in negative performance with studies showing 20% loss in the power output after a dust storm [4].

1.1.2 Non-uniform dust deposition

When dust settles on a surface, it can settle in such a way that all areas of the surface have the same amount of dust deposition; or in a way that the amount of dust deposition varies from one area of the surface to another. For a solar array, the ideal case would be where all areas of the solar array have the same amount of dust deposition. However, in practice, the amount of dust deposition has been found to vary. An example is when more dust gathers at the corners and edges of solar panels while the rest of the areas have less dust deposition [8]. Another example is when light rain falls on a dusty tilted solar panel, causing mud formation that trickles down the solar panel [9]. The variation of non-uniform dust deposition can be vast. In this study, a simple description of non-uniform dust deposition is presented, where the dust deposition varies from one solar panel to another. This means that on one solar panel, the density of dust deposition is the same, but different from other solar panels in the same PV array. In past studies, the studies that focused on dust deposition did not go into details of how the dust was spread on solar panels. Studies on non-uniform spread of dust deposition show that it negatively affects the performance of solar panels in a significant manner.

One of the performance characteristics affected is the transmittance. Non-uniformity can cause the transmittance of solar panels to reduce differently on various parts. This observation was made after rain fell on dusty solar panels, but was too little to wash off the dust, and instead created mud streaks

[9]. Solar panels at higher tilt angles had the least non-uniform variation of 0.21%, as the mud flows down faster. Solar panels at lower tilt angles had the highest variation 4.39%. Mud is thicker and thus results in more transmittance loss as compared to dust. The negative effect of non-uniform dust deposition become more significant when clean and dusty solar panels are connected to form a PV string. The connected PV string exhibits significant losses in the short circuit current as well as the operational voltage [8]. The power output also reduces due to non-uniform dust deposition. In a study in US Southwest region, non-uniformity was shown by the dust gathered at the bottom of the solar panel [10] and resulted in 10% power reduction. When the study was extended over a longer study period, rainfall cleaned the top part of the solar panel, leaving the bottom parts soiled thus creating another non-uniformity pattern [11]. The power output however still remained suppressed.

The information presented in this section shows that dust deposition and non-uniform dust deposition has negative effects on the performance of solar panels. How then can these effects be reduced?

1.1.3 Literature review on cleaning of solar panels

Cleaning the dusty solar panels has become a popular preventive maintenance action for dusty solar power plants. Existing solar panel cleaning approaches include use of electrodynamic screens (EDSs), solar panel coating, use of natural resources such as rainfall and wind, and manual cleaning: dry cleaning using brushes or clothes and wet cleaning using collected water. The EDS cleans fast and restores the power generation capacity of the solar panel as shown in [12]. However, dust particles with diameters less than 20 μm and those stuck to the surface persisted after EDS cleaning. Under dusty conditions, coatings has been found to result in lower transmission reduction as compared to bare solar panels [13, 14]. Coatings have been found to also be effective in simulated environment of Mars [15]. Frequent heavy rainfall can be relied on to clean solar panels [13], while light rainfall in a dusty area forms sticky mud on the glass surface thereby deteriorating the power output further [6]. Strong wind sometimes works effectively in cleaning solar panels, especially at larger tilt angles [16], but wind can be scarce and unable to remove dust particles whose diameters are shorter than 50μm since they tend to adhere to the solar panel surface [17]. Dry manual cleaning is used in areas where water is inaccessible. It saves on water and is less costly. It includes the use of mechanical brushes, microfiber-based cloth wiper and vacuum cleaners for cleaning [18]. Use of microfiber cloth has been seen effective in terms of dust removal. Wet manual cleaning is widely preferred in many large-scale solar PV plants. As cleaning with water is both a water consuming and labour intensive process, PV plants owners tend to plan the solar panel cleaning strategy in a cost-effective manner. However, without understanding the dust deposition process, many existing studies [19, 20, 21, 5] suggest a fixed-term weekly cleaning strategy, which is not cost-effective.

In order to effectively alleviate the negative impacts of the dust deposition on the solar panels, many research activities have been conducted to study the dust deposition dynamics with considerations of solar panels' materials, tilt angles, and geographical locations. The main purpose of these investigations is to build mathematical models that describe the show how dust deposition affects solar panel performance characteristics while considering influencing factors. The influencing factors include tilt angle, dust particle properties, and environmental and weather conditions. These dust deposition models are further used to predict the power generation losses from the solar panels. In the literature, the dust deposition dynamics are mainly modelled by three approaches, namely analytic approach based on first principle, regression analysis based on experimental data, and computer aided simulation. An analytical model developed in [22] to determine effects of dust deposition applied the Lambert-Beer-Bouguer law together with Monte Carlo simulation. The study concluded that the transmittance is decreased exponentially in relation to the dust deposition density. Several regression models have been developed to characterise the relationship between the transmission reduction and dust density, with the support of physical experiments. Experiments in [23] reveal that dust particles having a diameter of 80 μm and an area density of 250 g/m^2 will reduce the PV power generation by 84%. In [24], a regression model developed shows strong correlations between the transmission loss and dust deposition density based on the experimental observations. An empirical correlation developed in [5] enabled the prediction of the transmittance loss for glass at a specified tilt angle. The study [20] proposed a polynomial regression model, which reflects how dust deposition density varies with transmittance loss. As the computational fluid dynamics (CFD) method has been broadly applied to explore the nature of dust deposition with wind air flow, it is also applicable for the investigations of the nature of dust deposition for solar photovoltaic systems installed on the ground. For instance, the studies [25] and [26] applied CFD to study how dust deposition processes and behaviors affected solar arrays mounted on the ground. The study concluded that dust deposition was more for solar panels at the front row of the solar array and less for the solar panels at the back. Solar panels at the back were therefore less affected. [26] focused more on the impacts of particle sizes as well as the tilt angles of solar panels.

These existing dust deposition modelling efforts have properly characterised the transmittance losses of dirty solar panels. Practically, the dust deposition is usually distributed unevenly across the surface of a single solar panel or in a large-scale solar PV array. The non-uniform dust deposition results in more significant losses in power output brought about by dust-induced shading effects on the solar panels [9, 10]. The in-field observations in [8] show that the more dusty areas will result in a higher temperature which consequently reduce the power generation efficiency. In addition, the non-uniformity would also cause a shift of the maximum power point for the solar panels. When dirty solar panels are connected together with less dusty ones in the same PV string, it would lead to much larger power losses due to the shift of MPPT.

The transmittance losses and the consequences of the non-uniform dust deposition have provided strong motivations to maintain the solar panels clean. Many existing studies have made significant efforts to determine the cleaning schedules for the soiled solar plants. Factors that come into play in determining the cleaning schedules include the cleaning cost and the loss incurred due to soiling. Since there is a trade off between the cleaning cost and additional solar power generation due to cleaning, the cleaning schedules for dusty solar panels can be optimised. In the literature, a number of studies suggest a fixed cleaning schedules with optimisation. For instance, [27] determines a fixed clean interval according to the predefined power loss and dust concentration levels on the solar panels. In [28], the optimal cleaning frequency is decided at the minimum of the ratio between expenditure on energy loss and cleaning, and additional revenue generated by solar energy sales with the panel cleaning efforts. Ref. [18] advises the best cleaning frequency on weekly basis according to field measurements of the improved solar power outputs. However, the study [29] comments that it is profitable to clean solar panel if the soiling rate is more than 7%, while the fixed weekly cleaning policy is too costly. A financial approach was used in [30] to developing a cleaning strategy for solar panels. The study used a Regression modeling and an Artificial Neural Network model to determine the variation of efficiency with exposure duration and ambient temperature. Some other studies used optimisations to find the best variable cleaning schedules over a certain evaluation period. In [31], optimal cleaning schedule is obtained by solving a mixed integer linear optimisation problem with the consideration of the solar plant's soiling state and rain event. And the study [32] applies a condition-based cleaning policy to clean the solar power collectors with the considerations of the rain probability and reflectivity degradation of the solar collectors.

From the literature review on the dust deposition modelling and cleaning scheduling optimisation for soiled solar panels, we observe that more research investigations are necessary to further improve the cleaning schedules of the soiled solar panels.

1.2 RESEARCH MOTIVATION AND OBJECTIVE

The motivation of this research lies in two areas: 1) non-uniformity of dust deposition and 2) cleaning of the dust from solar panels. Non-uniform dust deposition negatively affects the power output from the PV systems making them less sustainable. Given that most solar PV farms are located in remote areas prone to dust, the challenge then lies in closely predicting the power output from solar panels prone to dust. After looking at previous studies, we found that more research is necessary on how non-uniform dust deposition occurs and its effects, so as to enable solar PV farm owners to closely predict the power output. The second motivation comes in when solar PV farm owners decide to clean the solar panels. Past studies have suggested that cleaning be done at fixed intervals or after events such as dust storms. In addition, all solar panels be cleaned at the same time. Considering the factors involved in cleaning such as frequency and costs of cleaning, the challenge lies in how to carry out the cleaning in such a way that the factors are balanced. We believe that there is way in which optimal cleaning can be done with a variable cleaning strategy.

This research is therefore presented with the objectives of:

1. Mathematically modeling of non-uniform dust deposition for solar PV arrays and describing the resultant effect on power output
2. Outlining a methodology for developing an optimal cleaning strategy considering the dust deposition dynamics and additional power generation due to cleaning. The optimal strategy provides:
    - Optimal cleaning frequency for solar PV arrays affected by non-uniform dust deposition.
    - Optimal cleaning intensity at each cleaning time for solar PV arrays affected by non-uniform dust deposition.

1.3 RESEARCH CONTRIBUTION

1.3.1 Journal papers

[1] D. Simiyu, X. Ye, X. Xia and Y. Hu, “Optimal cleaning strategy of large-scale solar pv arrays considering non-uniform dust deposition,” *Applied Energy*, 2019 (Submitted to journal on December, 1 2019)

1.4 DISSERTATION OVERVIEW

In Chapter 1, dust deposition and non-uniformity of dust deposition on solar panels are introduced. The contributing factors and effects of dust deposition and non-uniform dust deposition are then discussed. Based on the effects discussed, a literature review on solutions to reduce the effects is presented. From the literature review, a research gap is identified and described. It is proposed that this thesis focuses on non-uniformity of dust deposition on PV arrays and optimization of a cleaning strategy for the affected PV array. The contributions that the research will bring are also identified. The author then clarifies the motivation and objectives of the research. A layout of this thesis is given at the end of Chapter 1.

In Chapter 2, preliminary knowledge on the main topics in this research are given, backed by review from past studies. First, is basics on solar radiation and its measurements. The solar PV system is then discussed by looking at the behavior of a PV cell, PV system performance parameters, PV technologies and the faults affecting PV systems. Next, dust deposition is defined and the factors that influence it. Its impact on PV systems and the mathematical models developed in past studies are also presented. Lastly in this chapter, non-uniform dust deposition is described looking at the non-uniform dust deposition patterns and the simulated impacts that non-uniform dust deposition has on solar panels.

Chapter 3 gives a thorough literature review on the main focus areas. The first focus area is non-uniformity of dust deposition on solar panels and the effects that previous researchers have identified. Since this research focuses on cleaning of PV arrays, the next focus area is cleaning methods proposed by past studies, giving their advantages and disadvantages. Cleaning by water is identified as the best method for cleaning of solar panels using water. Cleaning strategies proposed for water cleaning are then outlined.

In Chapter 4, the proposed optimal cleaning strategy is developed and the optimization results given. The development starts with mathematical modeling of a solar PV array built from the single diode PV cell model. Using mathematical equations and Monte Carlo simulation, non-uniform dust deposition patterns are developed. Optimization of the proposed cleaning strategy is then done by developing an optimization model as follows. The objective function of the optimization is maximization of the net benefit associated with the cleaning of dirty solar panels in a solar plant. The decision variables are the number of dirty solar PV strings to be cleaned at each cleaning interval. The physical boundaries, the required power generation level, and budget limits are aptly formulated as the constraints for optimization problem. The formulated nonlinear constrained optimisation problem is properly solved using the "intlinprog" function in the MATLAB optimisation toolbox. The optimization model is applied to a case study consisting of 100 poly-crystalline solar panels to evaluate its effectiveness. Optimal solutions to the case study show that maximum net benefit is achieved by applying the optimal cleaning strategy, as compared to the "full cleaning", "no cleaning" and "random cleaning" solutions.

Chapter 5 concludes the thesis by looking at the achievements of the research and the research areas that can be focused on in future research areas.

CHAPTER 2 PRELIMINARIES

In this chapter, preliminary theoretical knowledge on topics such as solar radiation, solar photovoltaics (PV), dust deposition and non-uniform dust deposition is presented. The theoretical knowledge is backed up by literature review from past studies to demonstrate how researchers have applied these topics to studies on solar panels and dust deposition. First, solar radiation is introduced together with how measurements are taken. Thereafter, solar photovoltaics is introduced by defining the solar PV cells, their performance parameters and mathematical modeling; together with the solar PV technologies available and the faults that affect solar panels. Next, dust deposition is introduced by first defining it, detailing the factors that influence it and then looking at the mathematical models that have been developed in past studies to describe dust deposition. Lastly, detailed description of non-uniform dust deposition and how it occurs on solar panels is given, together with its impacts.

2.1 SOLAR RADIATION

The sun generates large amounts of radiant energy. This energy travels through space as radiation to the earth's atmosphere.

2.1.1 Components of solar radiation

As the radiation travels through the atmosphere it is divided into different components including:

(i) **Direct radiation:** is the part of the sun's radiation that falls directly on a solar panel from the sun.

(ii) **Reflected radiation:** is the part of the sun's radiation that falls on the ground and is then reflected to the solar panel.

(iii) **Diffuse radiation:** is the part of the sun's radiation that is first dispersed by particles in the atmosphere and then falls on the solar panel.

The quantity of solar irradiance reaching the solar panel also depends on factors such as the weather conditions, air mass, season in the year and air pollution. The weather condition is characterized by cloud cover, rain and snow, all of which can reduce or block the amount of irradiance that reaches the solar panel. Air mass is the quantity of atmosphere that light passes through to reach a surface. When the sun is directly overhead, the air mass is equal to zero. At this point too, the angle between the position of the sun and the vertical, in relation to the earth, known as the zenith angle, is zero. As the zenith angle increases, the air mass also increases. Increase in the value of the air mass reduces the quantity of solar radiation that gets to the ground. Seasons in the year include summer, autumn, winter and spring. In summer, the path of the sun is longest hence more sun hours, while in winter the path is shortest hence lesser sun hours. Air pollution causes particles in the atmosphere to scatter the sun's rays, thereby affecting the radiation that is received on the ground.

Given these factors that affect solar radiation, the amount of irradiance that reaches the surface of the solar panel at any place can be best known by carrying out measurements in the area of interest.

2.1.2 Measurement of solar irradiance

The radiation that reaches the earth is measured by the instantaneous amount that hits a square meter W/m^2, and this is also known as irradiance. Irradiance integrated over time is known as irradiation and is measured by kWh/m^2. Irradiance is grouped into different types which include:

(i) *Direct Normal irradiance (DNI)*

DNI is the amount of solar radiation per unit area received on a surface that is perpendicular to the rays of the sun which come in a straight line from the sun. Measurement of DNI is required in concentrated PV applications.

(ii) *Diffuse Horizontal irradiance (DHI)*

DHI is the amount of solar radiation per unit area received on a surface, not on a straight path from the sun, but dispersed in the atmosphere by solid objects, clouds and molecules in the sky. Measurement of DHI is important in fixed PV installations.

(iii) *Global Tilted irradiance (GTI)*

GTI is the total irradiance received by a tilted surface. It sums up the diffuse, reflected and direct radiation. It is mostly used in fixed tilted tilted PV installations to estimate the energy yield, but can also be used in tracked tilted PV installations.

(iv) *Global Horizontal irradiance (GHI)*

GHI is the total amount of irradiance that is received by a horizontal surface. It includes both the DNI and DHI. GHI can not be measured directly and is calculated using Equation 2.1

$$GHI = DHI + DNI(cos(\theta)), \tag{2.1}$$

where θ is the solar zenith angle. Measurement of GHI is important in fixed PV applications.

In order to determine the energy yield from solar panels, it is important to accurately measure and analyze irradiance components at the PV plant site under study.

2.2 SOLAR PHOTOVOLTAICS SYSTEM

The basic unit of a solar PV system is the PV cell.

2.2.1 Solar PV cell

The PV cell is the electrical device that generates electricity from solar radiation. PV cells are made of at least two layers of semiconductor material of which one layer is positively charged and the other layer negatively charged. When the PV cell is exposed to light, electrons are dislodged from the semiconductor and flow forming an electrical circuit. PV cells are quite fragile and are sandwiched between a transparent front sheet and a back sheet for protection. PV cells can be electrically connected to form PV strings which are then connected to form PV arrays.

To analyze the behavior of a PV cell, equivalent circuits are used. The equivalent circuit of a PV cell has been described by connecting together various components to form models. The models include the single diode model, Simplified single diode model, Ideal single diode model and the double diode model. The most common model used in solar PV studies are the single diode model and the double diode model. The single diode model has been found to be both simple and more accurate as compared to other models [33]. The model parameters include the light-generated current (I_L), one diode (D_1), shunt resistance (R_{sh}), series resistance (R_s), PV cell current (I) and PV cell voltage (V). These parameters help to characterize the performance of PV cells.

2.2.2 Solar photovoltaic performance parameters

Solar PV parameters include:

(i) Short circuit current, I_{sc}

The short circuit current refers to the maximum current through the PV cell when PV cell voltage is zero.

(ii) Open circuit voltage, V_{oc}

The open circuit voltage is the maximum voltage across a PV cell when the current though the PV cell is zero.

(iii) Power output, P_{out}

The power output is the product of the current and the voltage generated by the solar panel: $P = I \times V$ The power output is different from the maximum power output.

(iv) Maximum power point (MPP), P_{max}

The maximum power point is the point on the P-V curve at which the solar panel gives maximum power output. At the MPP, the output current and output voltage are I_{mpp} and V_{mpp} respectively.

(v) Fill factor, FF

The fill factor refers to the ratio between the maximum power and the product of the short circuit current and the open circuit voltage. FF is given by the Equation:

$$FF = \frac{I_{mpp} \times V_{mpp}}{I_{sc} \times V_{oc}} \tag{2.2}$$

(vi) Efficiency, η

The efficiency of a PV cell refers to the quantity of solar radiation that is converted into useful energy by a PV cell. It is expressed as:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{I_{mpp} \times V_{mpp}}{P_{in}} = \frac{I_{sc} \times V_{oc} \times FF}{P_{oc}} \tag{2.3}$$

(vii) Performance ratio, *PR*

The performance ratio (PR) is determined by the real energy produced by a solar panel and the energy that the solar panel would have produced had it had no losses. The PR is given by the Equation:

$$PF = \frac{Y_A}{Y_r} \tag{2.4}$$

$$Y_A = \frac{E}{P_{STC}} \tag{2.5}$$

$$Y_r = \frac{H}{G} \tag{2.6}$$

where Y_A is the real yield, Y_r is the reference yield energy at STC conditions, E is the real energy generated, P_{STC} is the nominal power, H is the total in-plane solar radiation and G is the in-plane solar irradiance at STC. The PR therefore gives and indication of the effect of system losses in the nominal power.

2.2.3 Mathematical modeling of a solar PV cell

Mathematical models describe the I-V and P-V characteristics of a PV cell. PV cell mathematical modeling is done using basic equations. The current from a PV cell is given by Equation 2.7:

$$I = I_L - I_d - I_{sh}, \tag{2.7}$$

where I_L is the light-generated current in Amps, I_{d} is the diode current in Amps, and I_{sh} is the shunt current in Amps. I_L is dependent on irradiance (G) absorbed by the PV cell and the cell temperature in $^{\circ}C$ and is given by Equation 2.8 [34]:

$$I_L = \frac{G}{G_{ref}}(I_{sc} + k_i(T_c - T_{c,ref})), \tag{2.8}$$

where G and G_{ref} are the real and reference irradiances respectively in W/m^2, I_{sc} is the short-circuit current in Amps at Standard Test Conditions of 1000W/m^2 irradiance, 25°C cell temperature and 1.5 air mass (AM:1.5). T_c and $T_{c,ref}$ are the real and reference temperatures respectively in Kelvin (K), and k_{i} is the current temperature coefficient in A/K.

The diode current I_{d}, is given by Equation 2.9 [35]:

$$I_d = I_{os}\left[\exp\left(q\left(\frac{V+IR_s}{AkT_c}\right)\right)-1\right], \tag{2.9}$$

where I_{os} is the saturation current, q is the electron charge in eV, V is the DC output voltage in volts, I is the output current in Amps, R_{s} is the series resistance in ohms, A is the diode ideality or shape factor and k is the Boltzmann constant. I_{os} has a strong dependence on temperature and can be expressed as in Equation 2.10 [35]:

$$I_{os} = I_{os-ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left(\frac{qE_g}{Ak}\left(\frac{1}{T_{c,ref}}-\frac{1}{T_c}\right)\right). \tag{2.10}$$

The shunt current I_{sh} is given by Equation 2.11:

$$I_{sh} = \frac{V+IR_s}{R_{sh}}, \tag{2.11}$$

where R_{s} is the series resistance, R_{sh} is the shunt resistance. Substituting Equations 2.9 and Equation 2.11 into Equation 2.7, the PV cell output current becomes [35]:

$$I = I_L - I_o\left[\exp\left(\frac{V+IR_s}{AV_T}\right)-1\right]-\frac{V+IR_s}{R_{sh}}, \tag{2.12}$$

where V_{T} is given by:

$$V_T = \frac{kT_c}{q}. \tag{2.13}$$

For a PV array with $\mathrm{N_{ss}}$ series and $\mathrm{N_{pp}}$ parallel connected solar panels, Equation 2.12 becomes [36]:

$$I = I_L N_{pp} - I_o N_{pp}\left(\exp\left(\frac{V+IR_s\frac{N_{ss}}{N_{pp}}}{AV_T N_{ss}}\right)-1\right)-\frac{V+IR_s\frac{N_{ss}}{N_{pp}}}{R_{sh}\left(\frac{N_{ss}}{N_{pp}}\right)}. \tag{2.14}$$

2.2.4 Solar photovoltaics technologies

Traditional PV cells were made from silicon. As research advanced, second generation PV cells were developed. They are made from amorphous silicon or non-silicon material such as cadmium telluride and are known as thin-film solar cells. Recent technological advancements have come up with third generation or emerging technologies which aim to increase efficiency and decrease the cost of PV cells. The emerging technologies include PV cells such as those made from mixed organic-inorganic halide perovskites and PV cells made from materials such a solar inks using printing technologies, solar dyes and conductive plastics. The solar PV technology can therefore be said to give a classification or variation of PV cells in terms of their radiation conversion efficiency and rates, manufacturing method and cost of manufacturing. Solar PV technologies in this study include mono-crystalline, polycrystalline, or thin-film as explained below:

(i) **Crystalline silicon**

- **Monocrystalline silicon (mono-Si)**
  Mono-Si PV cells are the oldest type of PV cells. The mono-Si PV cells are manufactured from one single crystalline ingot thereby retaining the purity of the crystalline structure. Their appearance is typically black or iridescent blue. The efficiency of light conversion of mono-Si PV cells is 26.1% [37]. They are also believed to be durable, lasting over 25 years. The efficiency of Mono-Si PV cells gradually reduces at a rate of 3% per year due to dust deposition alone [38]. The PV cells also have a complicated manufacturing process which raises their cost. They are also brittle making them vulnerable.

- **Polycrystalline silicon (poly-Si)**
  Poly-Si PV cells or multi-crystalline silicon are manufactured by combining multiple plates and grains of silicon crystals into thin wafers. The efficiency of poly-Si PV cells is therefore lower than mono-Si PV cells. The efficiency of poly-Si is slightly lower than mono-Si, at about 19.5% [39]. The appearance of poly-Si is mosaic-like. Poly-Si PV cells are the dominating technology in the market today as they are cheaper to produce and have a long lifetime of more than 25 years. Like mono-Si PV cells, poly-Si PV cells are also mechanically brittle and have a low efficiency of conversion.

(ii) **Thin film**

Thin film PV cells are much thinner than the crystalline silicon PV cells. They are manufactured by depositing a silicon film onto substrate such as glass, polymer or metal [40]. The amount of silicon used is therefore less which results in reduced costs. Less silicon however negatively affects the PV cell efficiency. Thin film PV cells are flexible and light in weight hence they can easily be integrated into buildings. Their flexibility is also improved as the thin film can be deposited on a variety of substrates. Thin film PV technologies include Amorphous silicon, Cadmium Telluride, Copper indium gallium selenide (CIGS) and Copper-Indium-Selenide (CIS) technologies.

- **Amorphous silicon (a-Si)**

  a-Si PV cells are the most developed of the thin film technology. a-Si material can be deposited on large and less costly substrate using continuous deposition techniques, making the manufacturing cost lower. a-Si PV cells however experience light induced degradation which results in power degradation over time to a minimum level. The efficiency of a-SI PV cells is about $4-8\%$ due to the LID [41]. After that, their performance becomes stable with light.

- **Cadmium Telluride (CdTe)**

  CdTe PV cells are made up of cadmium and tellurium. The cost of production of CdTe is lower and it higher efficiency (more than 15%) [42] as compared to a-Si PV cells. The efficiency is high due to their ideal band gap of $1.45eV$. Improvements have been done on the CdTe PV cells that have resulted in improved conversion efficiency of 22% [43]. CdTe PV cells have lower cost per kWh making them quite popular. The other advantage is that they are able to capture shorter wavelengths of light as compared to silicon PV cells. A concern about the technology is that Cadmium is toxic to the environment.

- **Copper indium gallium selenide (CIGS)**

  CIGS has been the most efficient of the thin film technologies. Their conversion efficiency has been reported to be 20% at laboratory level [44], which is the best of other thin film PV technologies. The downside with CIGS is the scarcity of indium which has negatively affected mass production process of the PV cells.

(iii) **Emerging photovoltaics**

Emerging technologies in PV cells aim to achieve high-efficiency devices at reduced manufacturing costs [45]. They also aim to use materials that are nontoxic and abundant. These properties can lead to more installations and can also make them more suitable for use in large-scale implementation of solar PV systems. Lately, a common example of emerging photovoltaics is the perovskite solar cell. Perovskites exhibit properties such as superconductivity, cheap production and manufacturing cost. Perovskites cells therefore boast of simplicity in fabrication, reduced production costs, strong solar absorption and higher power conversion efficiency of up to 22.7% for perovskite solar cell using poly(3-hexylthiophene) material [46]. The main problem with perovskites is that they are prone to rapid degradation on exposure to ultraviolet radiation and moisture. Lead is also a major component of perovskites cells which raises the levels of toxicity in the process of fabrication, use and disposal [47].

2.2.5 Faults affecting solar panels

The performance of solar panels can be hindered by factors such as light induced degradation, shading, discoloration, cracking and breakage, hot spots, among others [48]. The factors are discussed as follows.

(i) **Light induced degradation (LID)**

LID refers to the negative performance that is exhibited by PV cells at the beginning of their use outdoors. LID mostly affects thin film technologies especially the a-Si and CdTe [41]. CIGS PV cells however exhibit high performance during the initial period of exposure to light before long-term degradation sets in. Such behavior highlights the importance of studying the initial behavior of PV cells so as to accurately estimate their energy production. LID is detected by monitoring and analyzing the I_{sc} and V_{oc} or the I-V characteristics.

(ii) Shading and dust deposition

Shading refers to a situation where the irradiance that reaches a PV cell is reduced or blocked. Examples of such situations is shadows cast on the solar panel. Shading can affect the whole PV cell or solar panel, a situation known as whole shading with shading being at 100%; or it can affect part of the PV cell or solar panel, a situation known as partial shading with shading being between 0% or 100%. Partial shading varies greatly in size and intensity, giving many possibilities to its explanation. The shading could cover a small spot on the PV cell or solar panel, be confined to the edges of a PV cell or solar panel, cover a half of the PV cell or solar panel, etc. The location, orientation and presence of objects around the solar panel determine the type and size of shading that the PV cell or solar panel will experience. Shading can be divided into two major classes: objective and subjective shading [49].

- **Objective shading**

  Objective shading is brought about by factors that are unavoidable such as cloud cover or cloud movement. Clouds get in the path of the sun thereby reducing the amount of irradiance that reaches the PV cell. Cloud cover and movement have been found to cause significant losses of up to 25% during transition of irradiance as moving clouds cast shadows on solar panels [50].

- **Subjective shading**

  Subjective shading is caused by factors which can be controlled. Subjective shading can be dynamic or static. Dynamic shading, also referred to as soft shading, is caused by shadows cast on PV cells and solar panels by buildings, trees, and other structures. Shadows move depending on the movement of the sun, hence the shading brought about is dynamic. To reduce negative effects brought about by such shadows, it is recommended to install solar panels away from objects that can cast shadows, or if possible, remove the objects that cause shadows such as trees. However, in the case where these two methods do not work, studies have suggested various techniques that spread the effects of the shading evenly thereby minimizing the overall effects. These techniques include making modifications to how PV strings are connected in a string-level inverter system [51], reconfiguration of arrays [52] and string level optimization [53].

  Static shading, or hard shading, is caused by anomalies around the solar PV system. Anomalies include bird's droppings, leaves, dust deposition, snow, etc. The shading is static because it depends on the initial position of the causing factor and it may not change with time unless an external force is exerted. Static shading has a significant effect on the irradiance that reaches the cell area, thereby affecting the short circuit current and the open circuit voltage of a PV cell [49].

Other studies have categorized shading into temporary and "permanent" shading. Temporary shading is caused by factors that affect the irradiance for a short time after which full irradiance is restored without external intervention. "Permanent" shading is caused by factors that continuously affect the irradiance reaching the PV cell until external intervention is applied to remove them. These factors include animal and bird dropping, dust, snow and leaves.

(iii) **Discoloration**

Discoloration refers to the change in color of the solar panel surface and of grid fingers. It is exhibited after solar panels have been in operation for a long period of time. Discoloration is brought about by high temperature, high UV radiation, quality of encapsulant, humidity insufficient adhesion between cells and the glass material [54]. Visual inspection is used to detect discoloration.

(iv) **Cracking and breakage**

Cracking and breakage occur during transportation, installation and maintenance. Such cracks can easily be detected by visual inspection. During manufacturing, cracks can also develop due to mechanical and thermal stress exerted on the solar panel. The cracks are however micro-cracks and can not be easily detected by visual inspection. Such cracks can be detected by electro-luminescence imaging. The micro-cracks increase in size with continued use [55]. Cracks can cause ingress of moisture to the PV cell thereby reducing the performance of solar panels. Cracks can also increase the chances of people suffering an electric shock during maintenance.

(v) **Hot spots**

Hot spots are high temperature regions on solar panels. They can be brought about by factors such as shading and high concentration impurities such as transition metals in one area [56]. Hot spots are also caused by partial shading of PV cells, damage or mismatched PV cells or interconnection failure. These cause factors result in the affected PV cell generating less current than the current in the PV string or getting damaged. Hot spots are detected using infrared thermography and light I-V curves.

2.3 DUST DEPOSITION ON SOLAR PANELS

Dust deposition refers to dust settlement on the top surface of solar panels. Solar PV farms can be installed in remote areas that have high solar radiation. Such areas are also at times dry, windy and dusty. The wind carries dust which can settle on solar panels. In other areas that are industrialized, air pollution from industries such as coal and cement can be carried by wind and settle on solar panels. The reduces or blocking the quantity of irradiance that penetrates to the PV cells. The reduction is known as transmittance reduction, which has negative effects on the performance of solar panels.

2.3.1 Factors that influence the dust deposition on solar panels

(i) **Location**

The location of the solar PV farm refers to the surrounding natural, human or industrial activities. Desert and arid areas are more sandy, while other areas may have more fine clay dust. Human activities such as construction, farming, and industrialization will also results in emission of different dust types. Dust from industries such as cement and coal is more fine and may have different effects on solar panels as compared to dust from farming activities.

(ii) **Environmental factors**

Environmental factors include the weather conditions and environmental disasters such as volcanic activity, sand storm, tornado, among others. Weather conditions include wind and rainfall. Wind can carry dust particles and deposit on the solar panels. It can also remove dust particles that have settled on solar panels, especially when the solar panels are installed at a higher level from the ground. Rainfall falling frequently and in abundance, can clean solar panels removing dust. However, when the area is too dusty and the rainfall is light and infrequent, the rainfall will mix with the dust deposited on the solar panels forming mud streaks. The mud streaks can be sticky and thicker than dust thereby resulting in greater loss in te transmittance [6]. Areas that experience sandstorm will have a lot of dust depositing on the solar panel in short time, causing sudden significant loss in performance. The same applied to when ash is released from volcanic activity and tornados.

(iii) **Dust characteristics**

Characteristics of dust include the type of dust and size. Dust types include inorganic dust such as silica and mineral dust such as coal and cement dust; and organic dust from plant and animals such as wood, pollen and animal droppings. The various dust types differ in physical properties such as size and the effects they pose on solar panels. Dust particles range in size from 1 to $100\,\mu m$. Mineral dusts such as cement and carbon are found to be smaller or finer in size [3], as compared to dust and organic particles such as pollen [13].

(iv) **Solar panel characteristics**

The characteristics of solar panels include the angle at which it is tilted, the technology of the solar panel and duration of exposure.

- **Tilt angle of solar panels**

  When the tilt angle of solar panels is 0°, the solar panel is horizontal and the entire surface faces upwards. The dust deposition at this angle is faster due to gravitational settling. The size of the dust particles at this tilt angle includes both small and large particles. The rate of transmittance reduction at the low tilt angles is therefore faster [20], [5]. Increase in the tilt angle may cause dust particles to slide off the surface due to gravity. This can lead to gathering of more dust particles at the bottom frame of the solar panel leaving fewer and or finer particles on the upper parts. The transmittance reduction at the larger tilt angles is therefore reduced.

- **Technology of the solar panel**

  Technology of solar panels considered in this study includes monocrystalline, polycrystalline and thin film. The three aforementioned technologies have different band gaps with a-Si and CdTe technologies having wider band gaps than c-Si and CIGS technologies. The solar panels with wider band gaps are more affected by dust deposition as compared to those with smaller band gaps [9].

- **Duration of exposure**

  The duration of exposure refers to the length of time that the solar panel is exposed to dusty conditions without any intervention to remove it. As the exposure period increased, the transmittance of solar panels has been found to reduce [5] due to continuous accumulation. Increased exposure period was also seen to increase the transmittance reduction in a study in India [20]. In the study, when the tilt angle was 0°, dust deposition was at $15.84\,g/m^2$ which resulted in transmittance of 12.38%. Increasing the tilt angle to 90° reduced dust deposition density to $4.48\,g/m^2$ which increased transmittance to 52.54%. In areas that experience dust storms, dust deposited increases during such events and in such a case, the exposure period may not really matter.

2.3.2 Effect of dust deposition on solar panels

How dust deposition affects solar panels has been determined by carrying out experiments and conducting field studies. It has generally been determined that dust deposition has a negative impact on the transmittance. The reduced transmittance then causes deterioration of the performance characteristics of the solar panel, including current, voltage, power and efficiency. The extent to which the performance characteristics reduce depends on influencing factors such as location, exposure period, tilt angle, PV technology and type of dust. As will be seen in the study outcomes detailed below, higher performance reduction occurs when there is longer exposure periods, small tilt angles and finer dust particles.

2.3.2.1 Effect on transmittance of solar panels

Dust deposition causes transmittance reduction, especially after long exposure periods. 20% transmittance reduction was observed after 3 PV systems tilted at 32° were exposed outdoors for 30 months in Santiago, Chile [31]. Particle concentration varied with weather season, with the concentration being higher in winter than in summer. Consequently, the effect of soiling in the winter season was observed to be more that the effect in the summer season. The soiling rate during winter was 0.79% while the soiling rate during summer was 0.35%. Increased soiling rate was also attributed to humidity which causes more dust deposit on the PV systems.

A shorter exposure period of 8 days resulted in 20% in the transmittance of polycrystalline solar panels in Xi'an, China [57]. This is in comparison to 20% transmittance reduction after 30 months in China [31]. The difference can be explained by the difference between dust deposition density in the two locations. It was interesting to note that although dust deposition causes reduced transmittance, the temperature of the solar panel reduced as the dust deposition increases. The temperature reduction was as a result of dust forming a layer on top of the solar panel, thereby reducing its exposure to heat from solar radiation. Reduced temperature resulted in reduced rate of the power output with increasing dust deposition being lower than the rate of transmittance reduction.

Dust deposition increasingly affects the transmittance of solar panels as the tilt angle increases. The transmittance reduction continues up to an upper limit beyond which any more dust deposition has no effect on the transmittance. The conclusion was made after a study in Minia, Egypt, where glass plates were exposed for 30 days [5]. Transmittance reduced by 21% after the 30 days. The study also showed that dust deposition increased as the tilt angle increased from 0° to 90°, showing how the tilt angle influences dust deposition.

2.3.2.2 Effect on short circuit current of solar panels

Dust deposition causes reduced short circuit current from affected solar panels. As the dust deposition increases however, a limit reaches beyond which the reduction in current becomes less sensitive to increasing dust deposition. The conclusion was made after a study in Kuwait where the short circuit current decreased significantly by 40% with increased dust deposition density [58]. This was after desert dust was sprayed on solar panels and the I-V characteristics monitored. The study also showed that when levels of dust deposition density went above 1.5 g/m^2, it caused a reduction in sensitivity of the short circuit current. This was because when the study began, dust particles settled directly on the surface of the solar panel. With increased dust deposition, the particles settled on top each other as the surface is already occupied, and the resultant reduction in short circuit current wass smaller. The maximum current was also noted to reduce, which resulted in reduced power output. The climate in Kuwait is characterized by sand and dust storms, having coarser dust particles. When the size of dust particle become smaller, as the case is with carbon dust particles, the reduction in short circuit current is more and at a faster rate [3]. The fast reduction is attributed to the fine size of carbon dust particles, making it easer for them to spread over the surface of the PV more uniformly.

2.3.2.3 Effect on the power generated by solar panels

The reduction in power output varies with the tilt angle, exposure period and size of dust particles. At smaller tilt angles, dust deposition causes more reduction in the power output as compared to larger tilt angles [20]. Increasing the exposure period also causes an increase in the loss in power output. solar panels in Saudi Arabia were cleaned then exposed outdoors [4]. Their power output reduced by 24.6% and by 45.9% after 3 months and 8 months of exposure respectively. However, it should be noted that high dust deposit reduces the solar panel temperature thereby reducing the rate of power loss [57].

Fine dust particles cause more significant reduction in the power output as compared to coarse particles. In Saudi Arabia, a desert environment, silicon PV concentrators were exposed to dusty conditions for one month [3]. It was observed that smaller dust particles had a more pronounced impact on the power output of solar concentrators as compared to larger dust particles. The power output reduced by 40% when cement dust deposition occurred and 90% when carbon particles deposited on the concentrators. The study brought out the significance of considering the type of dust that deposits on PV surfaces and the effect of dust particle size.

The negative effect of dust increases with major dust events such as dust storms. In Saudi Arabia, the power output of outdoors solar panels continuously reduced in 6 months of outdoor exposure. A reduction of 49% was noted for polycrystalline solar panels and 44% for monocrystalline solar panels [4]. A sudden loss of 20% in the power output was observed after a sandstorms. The sandstorm affected all the PV technologies in the same way. Reduction in power output only stopped when rain fell and when cleaning was done.

2.3.2.4 Effect on the efficiency of solar panel

Efficiency reduction for solar panels affected by dust deposition, depends on the PV technology, quantity and type of dust deposited. 34% reduction in efficiency was observed for a dusty solar panel [58]. As dust was deposited, the efficiency reduced steeply and linearly. As the level of dust deposition increased past 1.5 g/m^2, the reduction was not as steep. The reduction in steepness or sensitivity was attributed to dust particles settling on top of each other as deposition continued. The reduction in efficiency also varies with PV technology. A study carried out in Egypt showed that the efficiency reduction for amorphous silicon was more than that of polycrystalline solar cells [24] for the same exposure duration. The amorphous silicon solar panels which were not cleaned for 6 months showed a reduction of 66% in the efficiency. The polycrystalline solar cells which were cleaned daily showed a reduction of 9% in the efficiency which was brought about by airborne dust particles, mostly cement. Amorphous silicon solar panels showed a reduction of 66% in the efficiency. A recommendation was made to carry out weekly cleaning. Reduction in efficiency due to dust deposition can therefore be said to vary with technology.

2.3.3 Dust deposition modeling

In the literature, the dust deposition dynamics are mainly modelled by three approaches, namely:

(i) **Analytic approach based on first principle**
An analytical model is developed in [22] by applying the Lambert-Beer-Bouguer law and Monte Carlo simulation to see how transmittance of solar panels varies with dust deposition. The study concluded that the transmittance decreased exponentially with the area dust density. Finer dust caused more reduction in the transmittance.

(ii) **Computational fluid dynamics (CFD)**
Computational fluid dynamics (CFD) is a computer simulation that permits the flow of dust around solar panels so as to analyze the effects. CFD method has been widely applied to determine nature of dust deposition in wind air flow, including ground-mounted solar panels [25] and [26]. CFD allowed the analysis of the air flow and dust deposition process around the solar panels. The rates at which dust deposited on the solar panels reduced from the first row to the back rows. The power output of the solar panels was affected in a similar manner. Study [26] focused more on how variation in dust particle sizes and tilt angle of solar panels and how they impacted dust deposition characteristics.

(iii) **Regression analysis based on experimental data**
Several regression models have been developed to characterize the relationship between the transmission reduction and dust density, with the support of physical experiments. The models were developed in different locations, under varying exposure periods and for different limits or levels of dust deposition. The models describe how dust deposition and transmittance vary with a few influencing factors such as tilt angle of the solar panel, exposure period and dust deposition quantity.

A non-linear correlation arrived at after a study in Minia, Egypt [5] was adopted for our study. We selected the correlation because the study was conducted over a long period of time, covering different weather seasons and involved a large amount of data. The correlation was arrived at after 3 mm thick glass samples were exposed on the rooftop for over a year. The one year period allowed data to be gathered for different weather seasons. The region is surrounded by agricultural fields, although it experiences low rainfall, below $50mm$. It experiences cold winters ($16°C$) and hot summers ($36°C$). The temperature difference between day and night is about $14°C$ which promoted formation of dew. Presence of dew on the solar panel promoted adhesion of dust particles to its surface. Results from the study showed that large reduction in the transmittance occur as the tilt angle decreases. Longer exposure periods for tilt angles that were less than 40° also resulted in significant reduction in the glass transmittance. The study concluded that when tilt angles $\beta \leq 30°$, dust deposition and its effects on transmittance differ with location and the prevailing weather conditions. The measured values of dust deposition were plotted against the measured values of transmittance. The plot showed that irrespective of the tilt angle, transmittance reduced as the dust deposition increased. The reduction was until a limit was reached beyond which any more addition of dust deposition did not have additional effect on the transmittance. The correlation given in Equation 2.15 was derived from the study.

$$\left(1 - \frac{T_{dusty}}{T_{clean}}\right)\% = 34.37\,\mathrm{erf}\left(0.17{\rho_D}^{0.8473}\right), \tag{2.15}$$

where T_{dusty} is the transmittance in dusty conditions, T_{clean} is the transmittance for clean conditions, erf is the Gauss error function and ρ_D is the dust deposition density. The advantage of the model developed by [5] is that it is quite robust as it was derived from a large amount of data which was collected over various weather seasons. For this advantage, the model is adopted for this study.

A polynomial equation was arrived at by Mastekbayeva and Kumar [24] during their study carried out in Bangkok. It involved artificially depositing different dust densities on a polyethylene sheet. Transmittance was obtained by measuring the irradiance above and below the sheet. The dust density $\rho_D\,(g/m^2)$ was plotted against the reduction in transmittance $\Delta\tau(\%)$ for dust sizes between 53 and 75 μm. The relationship in Equation 2.16:

$$\tau = 23.27ln(\rho_D) - 23.5, \qquad 5 \leq \rho_D \leq 15. \tag{2.16}$$

The plastic-covered samples were also exposed outdoors for 1 month during summer to allow for natural dust deposition. The samples were placed at 15° facing south. Measurements of solar irradiance were taken above and below the plastic sheet at 11 am, 12 pm and 1 pm for one month. The ratio of transmittance of a dirty sample to the transmittance of a cleaned cover was defined as the dust correction factor (DC). A correlation between the DC and the number of exposure days was obtained as in Equation 2.17 [24]:

$$DC_{15} = 0.0001N^2 - 0.0082N + 0.0999, \qquad 0 \leq N \leq 30, \tag{2.17}$$

where DC_{15} is the dust correction factor for a sample tilted at 15° and N is the exposure duration in days. The absorbed solar radiation H_a was estimated by Equation 2.18

$$H_a = H(\tau\alpha)DC, \tag{2.18}$$

where H is the total radiation incident on the surface. The model allows for estimation of transmittance given the amount of dust deposition and exposure duration. It restricts the use to solar panels tilted at angles of 15°. The data for the study was also collected over a short period of time.

A polynomial mathematical model was developed after an outdoor study in Cairo, Egypt [20]. The area is industrial with 4 cement factories and engineering industries. Weather conditions in the area is characterized by hot, dry and dusty winds and dust storms The composition of dust deposited during dust storms was said to be uniform and similar to the dust deposited during normal conditions. Temperature difference in the area is approximately $12.6°C$, which favors the formation of dew at in the morning. The area experiences low rainfall of about $18\,mm$ per year. In the study, glass samples at different orientations and tilt angles were exposed outdoors for 7 months. Values of dust deposition and transmittance were measured. A plot of the dust deposition vs transmittance was done which showed. The graph showed that the transmittance reduction increased as dust deposition increased until it reached an upper limit beyond which any more increase in dust deposition did not have an effect on the transmittance. A simple correlation was derived from the graph such that:

$$\Delta\tau = 0.0381\rho_D^4 - 0.8626\rho_D^3 + 6.4143\rho_D^2 - 15.051\rho_D + 16.769. \tag{2.19}$$

A linear relationship was developed for levels of dust deposition below 1.5 g/m^2 [58]. This was after desert dust was spread on a solar panel in a lab. Reduced transmittance of the dusty module caused the short circuit current and maximum power output of the solar panels to reduce by 40% and 34% respectively. The study also showed that when dust deposition density increased past 1.5 g/m^2, the sensitivity of the short circuit current to dust accumulation started reducing. The efficiency of the solar panel was also observed to reduce steeply and linearly as dust deposition increased. The reduction was however less steep for dust levels greater than 1.5 g/m^2. The behavior was due to dust particles falling on top of each other rather than on the surface of the panel. The slope of the curve was determined by:

$$k = \frac{\Delta\eta}{\Delta M}, \tag{2.20}$$

where $\Delta\eta$ is the change in efficiency and ΔM is the change in the amount of dust deposition in g/m^2. k was calculated to be 0.33 for each gram per meter square of dust deposition. The equation to predict efficiency was then found to be:

$$\Delta\eta = 0.33\Delta M. \tag{2.21}$$

2.4 NON-UNIFORM DUST DEPOSITION

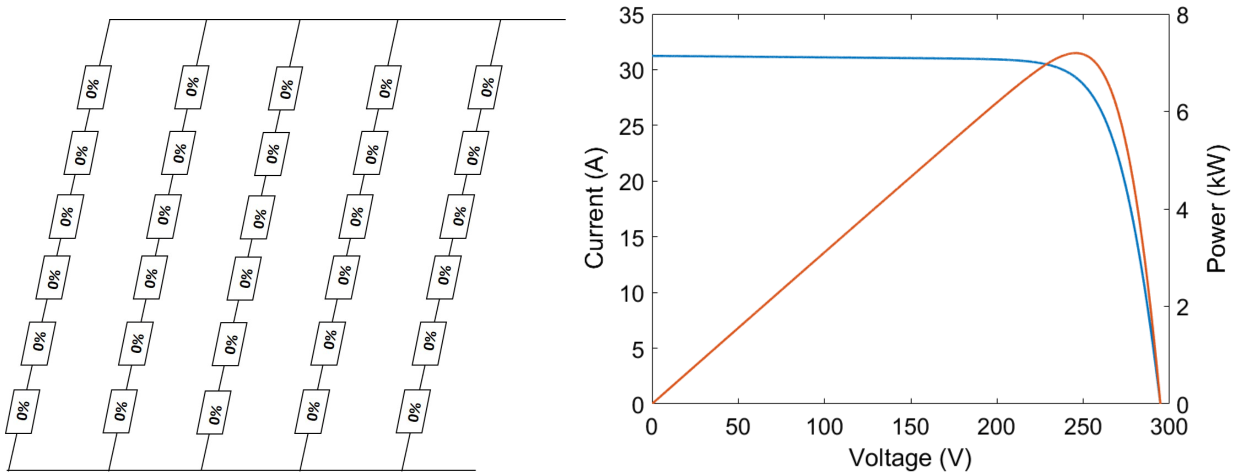
Non-uniform dust deposition is described as a state where there is variation in appearance or characteristics of dust on a solar panel. The variation comes about when dust deposition is influenced by factors described in Section 2.3. The variation in dust deposition can be described as non-uniformity patterns. Non-uniformity has negative effects on the performance parameters of solar panels.

2.4.1 Non-uniformity dust deposition patterns

Non-uniformity dust deposition patterns refer to how dust settles on the solar PV array to bring about non-uniformity. One of the patterns is when dust settles at the edges of solar panels, especially for framed solar panels. The pattern develops mostly when solar panels are tilted, framed and when the area has large dust particles. The dust particles can roll down the solar panels due to gravity, settling at the edges. The rest of the solar panel could also be dusty, although not as much as the corners. Non-uniformity pattern are also formed when dust settles in the space between the PV cells and the solar panel frame, while the rest of the solar panels has less dust deposition. In addition, when there is light precipitation in a dusty area, the rain water can be enough to mix with the dust deposited on solar panels and wash it downwards, but not enough to totally clean the solar panels. This behavior forms mud streaks. The mud streaks formed on solar panels causes non-uniformity patterns on the solar panel. Lastly, non-uniformity patterns can form when the quantity and spread of dust deposition varies from one solar panel to another in a solar array. In an array, non-uniformity of dust deposition can occur when clean and dusty solar panels are connected in the same PV string as shown in Figure 2.3(a). The patterns formed by non-uniform dust deposition are therefore vast and complex in nature. In this study, a simple non-uniformity pattern is presented, where the dust deposition varies from one solar panel to the other. The dust deposition on the same solar panel is however uniform.

2.4.2 Impact of non-uniform dust deposition on solar panels

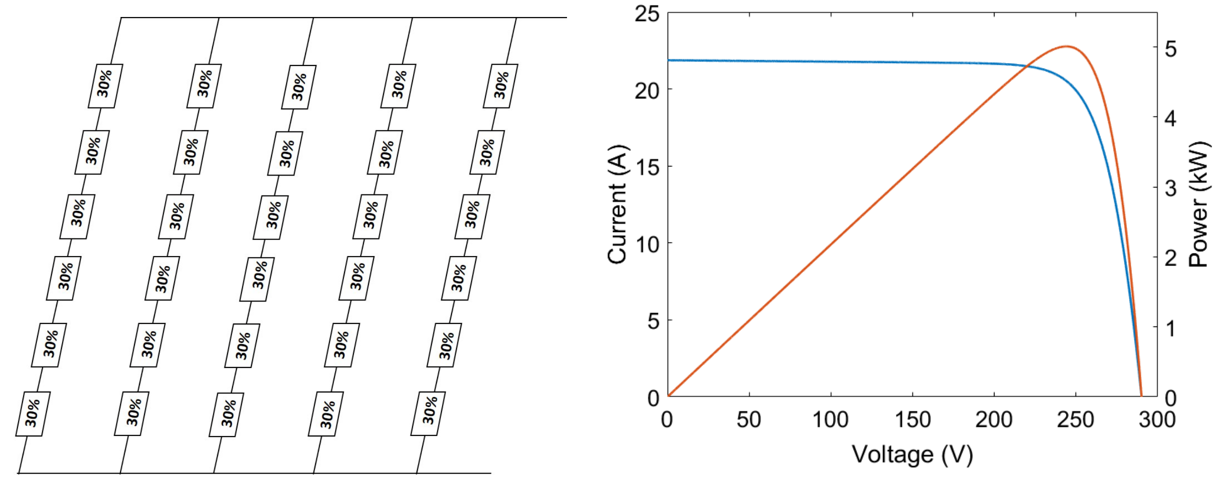
Dust deposition has negative impacts on the performance of solar panels as outlined in Section 2.3.2. To demonstrate these effects, consider a solar PV array with 30 solar panels given in Figure 2.1(a). At the start, all solar panels are clean and the I-V and PV curves are as shown in Figure 2.1(b). Maximum power is generated form each solar panel and from the PV array. Maximum current can be approximated to be 29 A, maximum voltage is about 248 V and maximum power output is about $7,192$ W. When the solar panels are covered in uniform dust deposition, such that all solar panels have



(a) Clean PV array **(b)** I-V and P-V characteristics

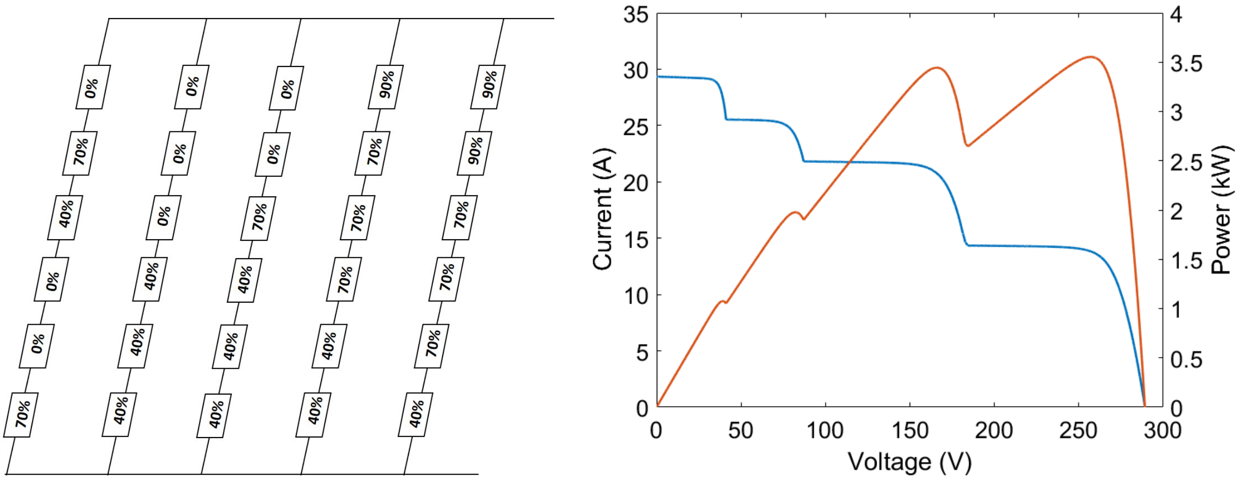
Figure 2.1. Clean PV array and its characteristics

the same amount of dust deposition, the irradiance received by each solar panel can be assumed to the more or less equal, with insignificant variation. The maximum current and power output begin to reduce as shown in Figure 2.2. Maximum current reduces to 20.8 A, maximum voltage is about 248 V and maximum power output is bout $5,158$ W. Dust deposition on the PV array can become non-uniform such that the amount of dust deposition varies from one solar panel to another. The irradiance received at each solar panel therefore varies according to the dust deposition received. The maximum current and power output are seen to not just reduce further, but multiple peaks also form on the I-V and P-V curves as shown in Figure 2.3. At the highest peak, maximum current reduces to 14..1 A, maximum voltage is about 262 V and maximum power output is bout 3,694 W.



(a) Uniformly dirty PV array **(b)** Corresponding I-V and P-V characteristics

Figure 2.2. Uniformly dusty PV array and its characteristics



(a) Non-uniformly dirty PV array **(b)** Corresponding I-V and P-V characteristics

Figure 2.3. Non-uniformly dusty PV array and its characteristics

When the dust deposition is non-uniform, studies have shown that the effects are more pronounced than when the dust deposition is uniform. The studies are presented in the literature review given in the next chapter.

CHAPTER 3   LITERATURE REVIEW

In this chapter, the past studies carried out on non-uniform dust deposition modeling and cleaning scheduling are reviewed. To start with, past studies on non-uniform dust deposition and its effects on solar panels are presented. Thereafter, the methods proposed in past studies to clean solar panels are presented. The advantages and disadvantages of the cleaning methods are given. The methodologies used to identify cleaning strategies in the past studies are outlined after which a conclusion is made.

3.1   NON-UNIFORM DUST DEPOSITION ON SOLAR PANELS

Studies on dust deposition have long presented dust deposition on solar panels without going into detailed description of how the dust is spread on solar panels or PV arrays. A few studies have shown that non-uniformity of dust deposition commonly occurs in areas that experience sand storms and in dusty areas with scarce rainfall. Some of the factors that influence the way non-uniformity of dust deposition occurs are the tilt angle of the solar panel, weather and environmental conditions. Weather conditions include the presence of dust and rain. When a dusty area experiences frequent rainfall, the rain water can wash away majority of the dust from the solar panels. However, when rainfall is scarce and in small quantities in a dusty area, the little rain water can mix with the dust on the solar panel forming streaks on top of the solar panels.

As described in Section 2.4, the way non-uniform dust deposition occurs can be said to be random and it results in a vast variety of patterns. Given such variability, it can be quite complex to determine a pattern that is suitable in describing the non-uniform distribution of dust deposition. Monte Carlo simulation comes in here to help in generating dust deposition patterns.

3.1.1 Monte Carlo simulation

Monte Carlo simulation refers to an algorithm that works by obtaining numerical results from a random distribution [59]. The resultant random numbers mimic an uncertain physical process. Monte Carlo simulation is widely used to model stochastic processes such as degradation, and reliability indices such as probability and frequency of failure. Such processes are complex to predict and lead to losses in costs. Since the processes are stochastic, the resultant costs also become stochastic. In order to run Mont Carlo simulation, it is important to first know the statistical distribution of the physical process under investigation. Examples of common distributions include the Weibull distribution, log-normal distribution, exponential distribution, among others. The distribution can be identified through curve fitting or from past records. Random numbers will be generated from the identified distribution. It is also important to have a mathematical model that defines the relationship between the random input and the corresponding output parameters. Simulations are run a number of times and the output analyzed and used in decision making.

Monte Carlos simulation simulates real situations and can be used to make predictions. It has therefore found application in risk analysis and quantification, sensitivity analysis and prediction. In maintenance, Monte Carlo simulation has been applied in developing maintenance strategies. The maintenance types focused on include preventive and condition-based maintenance. In order to develop any maintenance strategy, information of the previous processes such as failures, degradation, availability, among others. Such processes can be unpredictable and non-linear. In the cases where the information was not recorded, it can be difficult to determine the maintenance strategy. Monte Carlo simulation comes in to enable simulation of data for such stochastic process.

In past studies, Monte Carlo simulation has been applied in simulating processes such as degradation, reliability which includes system availability, probability, frequency and mean distribution of failure. These processes are assumed to be stochastic. For boilers, Monte Carlo simulation was applied in estimating the optimum period of time between maintenances for boilers [60]. The overall aim was to achieve maximum availability of the boiler. The system's availability was simulated using Monte Carlo simulation. This included the expected number of failures, maintenance actions and expected mean time to repair. By running several loops, the performance of the system in real life was estimated. From the statistical results obtained, the system performance in terms of the time between maintenances was determined.

Monte Carlo simulation has also been applied in developing a maintenance replacement strategy for a component subject to degradation though crack growth [61]. Uncertainty in the components was in the degradation process of crack propagation, which was seen to be non-linear. Crack propagation worsens with stress and can lead to component failure. The component crack propagation was estimated using Monte Carlo simulation. By estimating the failure probability of the component and the corresponding cost of replacement, a replacement of the component was determined. The optimal number of transformers to be replaced was also determined using Monte Carlo Simulation [62]. Specifically, the reliability of the working transformers was determined using Monte Carlo simulation after which the optimal number of spares was determined. The aim of the study was to minimize the cost of investment, damaged equipment replacement, interruption and no-billing costs. Monte Carlo simulation was used in estimating the reliability if the transformers in terms of their probability, frequency and mean distribution of failure. Exponential distribution was used to model the operating times until a failure occurred. The corresponding costs were also determined and ensured to be minimum.

Predicting of the remaining useful life of power electronics was also achieved by using Monte Carlo simulation to generate their degradation paths [63]. Degradation of the electronic components was indicated by measurements of the collector emitter voltages, which was assumed to be random. Gamma, Exponential and Poisson distributions were used in modeling the degradation process which helped in prediction of the remaining useful life of the components.

In the studies presented, Monte Carlo simulation has been used successfully in prediction of stochastic processes, which helped in making decisions on maintenance strategies. It can also be noted that the researchers have knowledge of the distribution that the physical process follows. Therefore, when it comes to maintenance, Monte Carlo simulation can be applied widely in areas where quantitative estimates of known distributions are required, making it suitable for use in this study.

3.1.2 Effects of non-uniform dust deposition on solar panels

The negative effects of non-uniform dust deposition on solar panels include significant losses in transmittance, power output, current and operational voltage. Studies also bring out the difference in negative effects caused by non-uniform dust deposition from the negative effects caused by uniform dust deposition.

3.1.2.1 Effects on transmittance

How much the transmittance reduces due to non-uniform dust deposition depends on factors such as the tilt angle of solar panels. Tilting solar panels causes non-uniformity of dust deposition to vary. Solar panel installations at larger tilt angles have less variation in non-uniformity as compared to those at smaller tilt angles. The conclusion was arrived at after exposing glass samples outdoors for one month in a study in Kuwait [9]. The glass samples were installed at various tilt angles. Rainfall was allowed to fall on the solar panels during the exposure period. Measurement of transmittance was done at the top part of the sample, middle and the bottom part. Transmittance was seen to reduce from the top towards the bottom, showing that non-uniform dust deposition was more at the top parts and reduced downwards. The glass sample tilted at 90° showed $0.1\,mg/cm^2\%$ variation in non-uniformity of dust density, while the those tilted at 30° showed a non-uniformity variation of $1.4\,mg/cm^2\%$ between top, middle and bottom parts. The highest variation in non-uniformity was observed for the sample at 0°. The variation of non-uniformity at various tilt angles can first be explained by the greater amount of dust deposition on solar panels at smaller tilt angles as compared to larger tilt angles. The second explanation has to do with the rain. When rain falls, larger tilt angles allow for the rain water to slide down hence creating a cleaner top and a dirtier bottom. The effects were observed for dust deposition levels below $19\,mg/cm^2$. When dust levels increased above $19\,mg/cm^2$, the effect was minimal. The study also brought out the behavior of various technologies with dust deposition. Wide band-gap thin film solar panels were seen to be more negatively affected than crystalline silicon solar panels. a-Si and CdTe solar panels showed 33% loss in the photocurrent for dust deposition density of $4.25\,mg/cm^2$. c-Si and CIGS solar panels showed reductions of 28.6% and 28.5% for the same dust deposition density.

3.1.2.2 Effects on operational voltage

The effect of non-uniformity on the operational voltage was realized after a study in a 192-kW PV park in Cartagena, Spain [8]. In the study, two solar panels were connected together. When both solar panels were dusty and measurements taken, the operational voltage and maximum power were found to have reduced. The solar panel with the highest dust affection exhibited a greater loss in operational voltage of 16.5% as compared to a loss of 11.4% for the other solar panel. The recorded voltage loss was also found to be larger than the voltage loss when the solar panels were considered separately. It was also observed that when the clean solar panels were connected together with dirty solar panels in one PV string, both the short-circuit current and operational were negatively affected; the losses in the operational voltage was however much more significant than the short-circuit current as compared to when the dusty solar panels were considered separately. The study not only brought out the effect of non-uniformity, but also the variation in performance for PV strings considered together and individually.

3.1.2.3 Effects on short circuit current

Past studies have used reduction in the short circuit current as an indicator of non-uniform dust deposition. However, in non-uniform dusty conditions, the variation of short circuit current was seen to be an unsuitable indicator when predicting the power output of solar panels. This conclusion was made after an outdoor study in the US Southwest region. In the study, Kagan et.al [10] crystalline silicon solar panels tilted at an angle of 7.5° were exposed outdoors for 7 weeks and measurements taken. Non-uniformity was observed as an accumulation of dust deposition at the bottom part of the solar panel. It was observed that the loss in the actual power was 10% while the loss in the short-circuit current was $4\% - 5\%$. Measurements were then taken for a solar panel installed in a landscape orientation and with non-uniform dust deposition. The I-V curve showed greater loss in the maximum power (7.6%) as compared to the loss in short-circuit current (4.6%). It was therefore concluded that the short circuit current is not accurate in predicting the behavior of non-uniformly soiled solar panels.

The study in the US Southwest region was extended to cover data over a longer period of 2-year [64]. The aim was to continue observing the behavior of the short-circuit current and the power output, but over a longer period. A more solid conclusion was made that the short-circuit current is not a true measure of non-uniform soling loss. Instead, power measurements should be used. In the study, two polycrystalline silicon solar panels were installed at a tilt angle of 5○. One solar panel was cleaned weekly, while the other was left uncleaned. It was observed that when rain fell, the dust on the uncleaned solar panel was not completely removed. The rain cleaned the top part and left other parts of the solar panel dirty. This type of cleaning led to the short-circuit current recovering while the power output remained suppressed. The short-circuit current loss was 1.9% compared to 3.7% for the power output. In addition, light rainfall was found to cause non-uniformity which resulted in power losses.

3.1.3 Conclusion

In the studies mentioned in this section, the negative effects of non-uniformity on the transmittance, short circuit current, operational voltage and power output are clearly seen. In real solar PV plants, non-uniform dust deposition is bound to occur. We therefore find that it is important to take non-uniform dust deposition into consideration when determining cleaning strategies for solar panels. In addition, the past studies have described non-uniformity using real pictures taken of solar PV plants and laboratory experiments. To the best of our knowledge, there are no mathematical models that have been proposed in the past studies to describe how non-uniformity of dust deposition can be simulated. This study seeks to fill the gap by proposing a method that enables simulation of a non-uniform dust deposition on solar arrays. The simulation will be useful in determining the cleaning strategy and the power output of solar panels and PV plants.

3.2 SOLAR PANELS CLEANING METHODS

In past studies, researchers have proposed cleaning as a way to reduce the effects of dust deposition. Cleaning methods from the past studies can be classified as self activating and externally activated cleaning methods.

3.2.1 Self activating cleaning methods

Self activating cleaning is where cleaning of a solar panel with dust deposition happens from the solar panels itself and physical human intervention is not applied. The methods are also referred to as self cleaning methods and include use of electrodynamic screens (EDS) and coatings.

3.2.1.1 Use of electrodynamic screens (EDS)

Electrodynamic screens (EDS) are transparent plastic sheets made of power electrodes implanted in a transparent coating. Dust particles on the EDS are removed when the electrodes are connected to an alternating voltage. Cleaning by EDS can therefore be said to be automatic and continuous. Cleaning by use of EDS has been found be effective in cleaning as it saves water, human labor and is environmentally friendly. EDS was found to remove up to 90% of dust deposition within two minutes [65]. Power generation of the solar panel was also restored to 98% of its original power after EDS cleaning. These qualities have created potential for EDS to be used in areas which have fine dust such as on Mars and the moon. It has also been determined that EDS can remove up to 90% of the dust stuck to the surface of a solar panel [66]. The conclusion was made after a study in which an EDS cleaning system was developed. The EDS system also repelled dust that approached the cover glass when it was operated continuously. The system was also found to be low cost and to consume less power and no water, therefore making it suitable for use in mega PV plants that are in remote locations.

EDS cleaning can also restore the reflectivity of a solar panel surface considerably. In a study conducted in Southwest United Stated, 12 EDS panels were monitored during dust removal [67]. From the measurements taken, EDS cleaning was found to maintain reflectivity of more than 90%, although a loss of 3.2% was noted. Removal of the dust was also done using $\leq 1\,Wh/m^2$ per cleaning cycle which is a small percentage of the energy generated by solar panels.

Challenges with EDS cleaning include cleaning dusty solar panels after rainfall, removal of fine dust and safety of operators. Rain falling on a dusty solar panel may cause formation of mud streaks when the rain is little. The mud adheres to the solar panel and may require some force to clean it. In such a case, the EDS system can be effective only after the mud has dried [66]. In addition, although EDS systems can remove dust and restore dusty solar panels to good condition, the technology does not remove the fine dust present on the surface. In a study in Qatar, dust particles lower than 20 μm were found to persist after EDS cleaning, while the other dust particles were removed [68]. It was also noted that the efficiency of EDS reduced at low dust accumulation levels. The efficiency of EDS at dust loading of 100 mg/m^2 and 200 mg/m^2 was noted to be 90% and 60% respectively. Since EDS screens are powered by the solar panel, the final power output of the PV plant was found to reduce by up to 15% [69]. When cleaning with EDS, there is also a threat of degradation of PV screen due to ultraviolet rays. Operation of the EDS needs high voltage which can be a safety hazard to operators.

3.2.1.2 Use of coating

Coating for solar panels is a covering that is applied on the top surface of solar panels. It serves various purposes including acting as an anti-soiling material or an anti-reflective material. The use of coating as an anti-soiling material creates another solar PV cleaning method. Coating on solar panels makes them either super-hydrophilic (SHIP) or super-hydrophobic (SHOP), making it easier to clean the PV surface. SHIP coatings work by spreading cleaning water and removing the dust by the water stream. SHOP prevents dust from sticking on the surface of solar panels and lets water flow of the PV surface more easily. They are more useful in dusty environments that experience plenty of rain.

Effectiveness of coating in removing dust from solar panels was demonstrated by exposing coated and uncoated solar panels for 1 year at 21° tilt angle [70]. The transmittance loss for the coated solar panels reached up to 10%, while the loss for uncoated solar panels was 12%. The yearly average daily energy soiling loss was also reported to be 2.5% for the coated solar panels and 3.3% for the uncoated solar panels. The coating was also found to be intact after the one year of exposure.

Coated samples were also found to perform better than uncoated samples a separate study in Belgium. The study involved multilayer-coated and uncoated glass samples tiled at 35° exposed outdoors for 3 weeks. The coated samples showed transmittance reduction of 0.85% while the samples with no coating showed a reduction of 2.63% [13]. It was unclear weather the tilt angle affected the performance of the samples. However, since the samples were subject to rain, the higher tilt angle could have allowed the water particles to fall thereby enabling better cleaning. The contribution of water in self cleaning by coating was further demonstrated in a study in Singapore. Bare and TiO_2-coated (titanium dioxide) glass samples exposed outdoors for 10 days. Rain was allowed to fall on the samples. After 10 days, the samples showed transmission reduction by 0.261% and 0.167% respectively per day [14]. Lower transmission reduction of the coated sample was attributed to the coating becoming conductive and highly hydrophilic thereby increasing its wetability and making cleaning better.

Recent developments in research include finding the best way to clean solar panels in Mars. Mars is covered in noticeable expanses of sand and dust. Solar panels are used to power spacecrafts to mars and are therefore prone to being dusty. Cleaning methods in mars include use of wind and gravity, though these are not effective due to factors such as low wind speeds. Using water is not possible in mars propitiating researchers to find an alternative. A recent interesting study investigated the use of coatings in simulated environment of Mars [15]. By simulating the mars environment, dust was deposited on coated glass samples. It was observed that samples with hydrophobic coatings partially restored dust removal performance.

The downside of the TiO_2 coating however is that it needs water or rainfall for it to be effective [13]. It is therefore not very suitable for use in dry and dusty areas. Washing off may also be necessary to completely restore good performance. Coating also increases reflection loss thereby reduces the performance of solar panels. Operation of EDS was also noted to be limited to RH < 60% as it requires generation of electric field which can be affected by moisture. Durability of the technology has also not been solidified yet.

3.2.2 Externally activated cleaning methods

Externally activated cleaning involves manual cleaning or use of natural resources external to the solar panels to remove dust. These resources include rainfall and wind. Manual cleaning can be dry or wet. Dry manual cleaning includes the use of brushes, clothes, compressed air and vacuum cleaners. Wet manual cleaning involves the use of water from the municipal council, personal water purifiers, etc. Both dry and wet manual cleaning can be automated.

3.2.2.1 Use of natural resources

Natural resources for cleaning include rainfall and wind. The cleaning is cost free, but is dependent on the weather conditions.

(i) **Rainfall**

Rainfall is relied on as the cleaning method in areas where it falls frequently and in abundance. Frequent and abundant rainfall provides sufficient water which allows for effective cleaning to happen at each rainy instance. Any amount of rainfall that surpasses $4-5$ mm has been found sufficient to clean solar panels [71]. This however may vary from location to location and depends on the size of the dust particles. Rainfall washes away dust from the surface of solar panels thereby resulting in an increase or restoration of transmittance, power output and efficiency.

In Northern California in the United States, exposed samples showed a decrease in efficiency until a time when there was a rainfall event (20 mm) that caused the efficiency to increase by 40% [72]. The efficiency was however not restored to the maximum value (partial recovery). Partial recovery is attributed to the inability of rain water to remove the dust particles which tend to stick to the surface of the solar panel. A study conducted in the Eastern part of Saudi Arabia showed that although rain fell on exposed samples and removed dust deposition, the power output of the PV system did not fully recover after such cleaning [4]. The partial recovery was caused by the inability of the rain water to remove small dust particles. The small dust particles tend to stick to the surface of solar panels making cleaning difficult unless some force is applied. The behavior of rain on small dust particles was also observed in a study in KU Leuven, Belgium [13]. In the study, glass samples tilted at different angles were exposed outdoors and measurements taken right after rain fell. The samples were also scanned under a microscope. The results showed that rainfall had a limited effect on small dust particles sized $2 - 10\mu m$; larger particles sized $> 60\mu m$ were however easily removed by the rainfall.

While rainfall can remove dust and cause restoration of performance, it can also contribute to deteriorating performance of solar panels. This is more so in areas that are dusty but have scanty rainfall. The amount of rainfall and dust deposited on a solar panel therefore determines how much cleaning will be done or how effective it will be. The effect of scanty rainfall was demonstrated in Kuwait, which has an arid climate with very low rainfall [6]. Solar panels exposed outdoors showed a loss of 25% in the daily yield after rain fell. The reason for the loss was formation of sticky mud on the surface of the solar panel which reduced the transmittance thereby deteriorating the yield. A similar observation was made in Berkeley, California [72], where it was noted that the efficiency of the system can decrease further following light rainfall. It can therefore be concluded that in areas where rainfall is frequent, cleaning by rainfall can be relied on. The cleaning may however not be 100% effective. A second conclusion is made that cleaning by rainfall in dusty areas becomes ineffective when the rain is scanty. The cleaning can also ineffective because rainfall can be unpredictable. When solar panels are tilted, cleaning by rain becomes more beneficial for higher tilt angles as they allow the water to fall off due to gravity, carrying the dust with it.

(ii) **Wind**

Wind can act as a natural cleaning agent. High wind velocity helps in carrying away large dust particles. Wind also helps to dry the moisture that forms on the PV surface thereby making dust particles less sticky to the PV surface. In addition, the cleaning effect of wind has been found to be more effective for at the height of solar panel installation from the ground increases [16]. However, cleaning by wind is ineffective for dust particles smaller than 50μm as they tend to adhere to the surface thereby resisting removal by wind [17]. Wind is also not very reliable as it is dependent on the weather conditions.

3.2.2.2 Dry manual cleaning

Dry cleaning includes the use of dry brushes, clothes, vacuum cleaners and compressed air to remove dust from solar panels. It is mostly used in areas where water is inaccessible. Dry manual cleaning is therefore less costly and environmentally friendly as it does not use water. Using dry brushes to clean dusty solar panels does improve the efficiency of the solar panels, just not to the original level. This observation was made after a study in Thuwal, Saudi Arabia [73]. Various cleaning methods including plain dry brushing and dry brushing with washing were used for exposed glass samples. Dry brushing restored the transmittance of the glass samples to about 90.67% of the original transmittance. When the brushed samples were washed with water, the transmittance was restored to 92% of the original transmittance. The lower performance of dry brushing was attributed to the presence of sticky particles which could be removed by use of a combined vacuum cleaner, some force or water. It was however noted that cluster defects and scratches were present on the glass samples after dry brush cleaning. The defects were however not significant enough to affect the optical transmittance. A solution to scratches caused by brushes is to use silicon rubber foam brushes which provide highly effective, nonabrasive cleaning [74]. Microfiber-based cloth wipers have also been found be highly effective in cleaning in terms of effectiveness, cleaning cost and time taken to clean, as well as when it is combined with a vacuum cleaner [18].

Compressed air has been used to blow dust particles off PV surfaces. In the UAE, [75] proposed a cleaning system that uses air current from air conditioner fans to blow over solar panels thereby removing dust and heat. The cleaning method was proposed for the area because it of its hot climate making the air conditioning the major electrical load in the area. The solution however works best for PV plants close to buildings such as rooftop PV installations. There may be an issue with dust dispersed during the cleaning process, especially in very dusty areas. Perhaps the use of a dust sucker could reduce dust dispersion.

The aforementioned studies show that dry cleaning does work for dusty solar panels. However it does not remove all the dust particles; the small ones tend to stick to the surface during cleaning. Use of water together with brushing is recommended. When compressed air and other blowing mechanisms are used to clean, they may results in significant suspended dust in the air. Dry cleaning is therefore not suitable for large scale PV plants, and for use in very dusty areas.

3.2.2.3 Use of collected water

Cleaning using collected water involves use of water from the municipal council, boreholes and other water storage units, with or without surfactants. The water may be used as is or treated through distillation, de-ionization and reverse osmosis before being used to clean. Treatment of water is preferred as it removes impurities from the water which can cause spotting and streaking on glass surfaces. Water that is rich with high mineral content may also leave deposits on the solar panel over time; water with low mineral content is therefore recommended. Since solar panels are exposed to the external environment, the temperature of water that is used in cleaning comes into play. Very cold or hot water may cause a sudden temperature difference leading to cracks on the solar panel. Cleaning early in the morning with ambient temperature water has been recommended. Cleaning by using collected water can also be done with pressurized or non-pressurized water, with or without surfactants. Use of pressurized water is effective, but a cleaning brush has to be used to remove sticky particles. The pressure of the water has to be kept below 4MPa (40 bar). A pressurized water system will also result in increased running cost as it requires a high pressure pump and power to move the water. The pressurized water falling on the solar panel also splashes and may result in wastage in the long run.

Studies have been carried out on the use of surfactants in cleaning solar panels. Surfactants are some of the compounds that make up a detergent. The word is derived from the word surface active agent. Surfactants are commonly used to remove dirt from household items. They work by breaking down the boundary between water and dirt. They hold the dirt in suspension thereby allowing for its removal. Surfactants can be anionic, cationic or zwitterionic. Past studies show that surfactants give better cleaning than when only water is used, thereby preserving or improving the performance of solar panels. Anionic and cationic surfactants give the most effective cleaning result regardless of the surface that has the dust deposition [76]. The behaviour of the surfactants was demonstrated in a controlled experiment, where sand and carbon particles were blown on a glass surface. Anionic, cationic or zwitterionic surfactants were then sprayed on the dusty glass surface and the behaviour observed. Anionic surfactant sprayed on sand and carbon particles removed the sand particles. Zwitterionic surfactant exhibited the same behaviour as the anionic surfactants only that it was slow in action. When carbon particles were deposited on the glass samples, neither the anionic nor the zwitterionic surfactant removed the carbon particles. Cationic surfactant spayed on sand and carbon particles removed the carbon particles but could not remove dust particles. When the anionic and cationic surfactants were mixed, both the sand and carbon particles were removed from the glass surface. The mixture was therefore found suitable for use in cleaning solar panels.

The effectiveness of anionic surfactants was also demonstrated when cleaning dirty solar panels in a study by Chaichan et al. in Egypt [77]. After using Sodium Dodecyl sulfate, an anionic surfactant to clean solar panels, the efficiency was found to stabilize. An efficiency loss of 1% was reported in the study after two months exposure. Alcohol was also reported to stabilize the efficiency and only 0.1% loss was reported.

Cleaning using surfactant (glass cleaner) was also found to result in stabilized efficiency as opposed to using just distilled water which resulted in efficiency reduction. The observation was made in Baghdad, Iraq where exposed solar panels were cleaned using glass cleaner [77]. From the study, the cell efficiency reduced by 14% when cleaning with water as a detergent was done. The reason for the reduction was failure of the water to remove small particles from the glass cleaner surface. When cleaning was done using a combination of anionic and cationic surfactants, efficiency of the glass cleaners remained almost constant and did not deteriorate. Use of surfactants also minimized the amount of water needed to clean the glass cleaners and the energy needed to spray water.

The influence of a pressurized and non-pressurized system for cleaning was demonstrated using a cleaning system that was set up in a German University in Cairo (GUC), Egypt for 6 solar panels [78]. For 45 days, the solar panels were first cleaned daily using water only, then cleaned using water and surfactants. The efficiency of the solar panels was measured for each cleaning methodology. It was observed that cleaning with water only caused a daily reduced efficiency of 0.14% and 50% after 45 days of cleaning.

A conclusion can therefore be made that cleaning solar panels with de-ionized water and surfactants gives the best cleaning technique. In many areas, dusty conditions still prevail but the cost of water is high. The question then arises, how frequently should solar panels be cleaned to maintain high power output levels and save water and labour? Researchers have answered this question by proposing cleaning strategies. The strategies are discussed in the next section.

3.3 SOLAR PV CLEANING STRATEGIES

Studies have been carried out to determine cleaning strategies for solar panels exposed to dusty conditions. These strategies seek to achieve various aims such as reducing the cost associated with soiling and cleaning and maintaining a required level of power output. The cleaning strategies can be grouped into two, namely:

- General cleaning strategies
- Optimized cleaning strategies

3.3.1 General cleaning strategies

General cleaning strategies include use of cost/benefit analysis and analyzing the way solar PV parameters are affected during dust deposition to help select a cleaning strategy.

Cost/benefit analysis involves looking at the economic operation of a solar PV plant. Cash inflow for the operation of the PV plant was compared with the costs incurred due to dust deposition. In a study, Pavan et al. [79] proposed the use of an economic index to help in selecting a cleaning strategy. The study involved two PV plants which had different cleaning procedures applied to them. One cleaning procedure used distiled water and a brush and the other used distilled water only. Measurements of power were taken before and after cleaning was done. Economic analysis of the two cleaning protocols was done to determine the protocol to adopt. The analysis involved comparing the cash inflow with the costs incurred for loss due to pollution and cleaning costs. The best cleaning strategy being the one where the benefits outweighed the costs.

Analysis of the PV parameters such as power output and efficiency due to dust deposition has also been used to determine the cleaning strategy. The analysis was done in a study where solar panels were exposed outdoors in the Eastern province of Saudi Arabia [4]. The exposure period was one and a half years, within which cleaning was done and measurements of power output taken. By analysis of how the power output reduced, a fortnight cleaning strategy was recommended. Analysis of efficiency was also done in an industrial area in Helwan, Egypt, which had high levels of pollutants from the desert and industrial plants [24]. The efficiency was noted to degrade to 66% after 6 months. Degradation rate of current was at 6.2% per month. Cleaning once every week and immediately solar panel at the required level. The approach of analysis the PV efficiency was also applied by Elminir et al. [20] and Hegazy [5] who recommended weekly cleaning and cleaning after every dust storm.

The studies presented in this subsection have used cost analysis and PV parameters to determine the cleaning strategy. The studies have however not fully explored the dust deposition process in determining the cleaning strategies, in addition to them proposing more or less a fixed cleaning strategy. This can result in very frequent cleaning and high costs or less frequent cleaning that becomes ineffective. The studies have also not explored how users can effectively make use of limited resources such as finances, water and labor to carry out cleaning. This gap has been partially addressed by studies that have proposed optimization approaches.

3.3.2 Optimized cleaning strategies

Optimized cleaning practices look at how to carry out cleaning in a way that ensures maximization of production and the minimization of costs associated with loss in production due to dust deposition and the costs related to cleaning solar panels. Optimized cleaning strategies can be divided into the use of thresholds and use of constrained mathematical models.

3.3.3 Use of thresholds (power, soiling and reflectivity level)

Use of thresholds includes determining the level beyond which soiling and power output levels should not go in order to maintain good performance of a solar PV system. Thresholds include soiling level, power output and reflectivity. The soiling level/threshold has been used to find the optimum point to carry out cleaning. For solar PV plants installed in the Sahara desert sites, the optimum soiling threshold for cleaning was found to vary for different PV technologies [29]. In the study, two technologies were considered; crystalline Silicon (Mono-Si) and Thin films (CdTe). Two cleaning protocols were considered; protocol 1 where cleaning for all solar panels was practiced on a weekly basis (weekly cleaning) and protocol 2 where cleaning all solar panels was done twice a year (bi-annual cleaning). For each PV plant, the energy produced and the performance ration were determined. Analysis done for the two technologies showed that for thin film solar panels, the optimum soiling level for cleaning was 6.8% and 7.3% for mono-Si solar panels. With the higher revenue, thin film solar panels can recover the cost used to carry out cleaning on them faster.

A threshold for power output was also determined in developing a cleaning strategy. In a study to find the cleaning strategy for solar panels in a desert environment [27], reduction of power output was used as a cleaning criterion. When cleaning went below 5%, which corresponded to $2g/m^2$ dust density, cleaning of the solar panels had to be done. A non-linear mathematical model was then used to determine the cleaning time. The size of dust particles also influences the cleaning frequency. When dust particle diameter is large, the cleaning frequency of solar panels is longer than when the particle diameter is smaller. A cleaning strategy was found to decrease from 12,512 to 7 days when the particle size increased from $1\mu m$ to $20\mu m$.

A time-varying reflectivity threshold has also been used to determine an optimal and flexible cleaning strategy [32]. Time variation allows for the changing conditions on the solar panel such as natural cleaning and changes in electricity prices to be considered. In the study, the goal of the optimization process was to minimize the loss due to cleaning and revenue lost as a result of reduction in reflectivity. The cleaning decision is made by comparing the actual measured reflectivity to the set threshold.

3.3.4 Constrained optimization models

Optimization of cleaning strategies has also been carried out using constrained mathematical models. One study optimized the cleaning policy by using a non-linear mathematical model [80]. The model compared the cleaning costs with the economic losses due to reduced performance (efficiency) of solar panels. The decision variable for the model was the maintenance interval. The model was constrained by the cost of production loss which had to be lower than the cost of maintenance. The model was applied to a case study Milan, Italy, where monitoring of a solar plant was done for two years. The economic losses due to soiling and costs due to cleaning were obtained from measured parameters. Applying the proposed model gave a cleaning interval of 5 months. In the proposed model, all solar panels were cleaned during each cleaning activity.

A non-linear model was also proposed for solar plants in Central Saudi Arabia [28]. The objective of the model was to minimize the cleaning cost. Optimization was done by balancing the revenue loss due to dust with the cleaning cost. The decision variable was the cleaning interval, where all solar panels were cleaned. The model restricted the soling level to levels below 11% as non-uniformity of dust deposition occurred during heavy soling. To apply the proposed model, on outdoor testing station consisting of 2 arrays of 12 panels each, tilted at 15° was set up. Some solar panels were cleaned regularly while others were left uncleaned. Soiling loss was obtained by using a mathematical model which considered the measured short-circuit current. Using the obtained soiling loss and an estimated cleaning cost, the optimal fixed cleaning strategies were determined for the various solar panel technologies.

Developing an optimal cleaning strategy was also found to be dependent on the case at hand. Cases varied depending on factors such as the effect of rainfall as a cleaning agent and the cost of cleaning. Variation in any of these factors will vary the cleaning strategy. This statement was arrived at after a study on soiling analysis in Santiago de Chile [31]. In the study, 3 PV systems tilted at 32° were exposed outdoors for 30 months. Manual cleaning was done on a monthly basis and rain was also allowed to fall on the solar panels. The soiling rate was determined by analyzing of the decrease in the performance ratio (PR). Based on the soiling rate, the economic impact of revenue and cost was determined. An optimal cleaning procedure was developed by balancing the energy sold with the energy lost due to dust deposition and the costs of cleaning. The optimization problem was formulated into a mixed integer linear programming equation with the objective of maximizing the production output, and was constrained by the number of cleanings for the control horizon and the soiling rate. The optimization problem was solved for two scenarios; with rainfall cleaning considered and without rain being considered. When considering rainfall, the optimal number of cleanings was 6, but without rainfall, the number of cleanings was 9. When the cost of cleaning was raised, the optimal results were 3 cleaning in the rain scenario and 6 cleaning in the scenario without rain. Variation of rainfall cleaning and cost of cleaning therefore had an effect on the optimal cleaning strategy.

3.4 CONCLUSION

The studies presented in this chapter show that cleaning of solar panels can be done through various ways. EDS and coatings offer self activating solutions for water-scarce and hard to access areas, making it possible to clean without human intervention. However, fine dust may still persist on the surface of solar panels after cleaning by EDS or coating. Sticky dust or mud will also stick after such cleaning. Dry manual cleaning using brushes and clothes offers less costly cleaning solutions. Brushes and clothes do not restore the performance of solar panels and may result in scratches on the surface of solar panels. Cleaning compressed air works best when energy is being recycled, and when the dust deposition is low. In large solar PV plants with high dust deposition, dust dispersion and energy to generate the compressed air become challenges to such cleaning. While rainfall and wind can offer cleaning solutions especially in areas where they are frequent and in abundance, they are dependent on weather conditions. They also do not fully clean solar panels to restore their original performance. This leaves manual cleaning by water as the best alternative for removing dust deposition. Past studies on cleaning by water suggest fixed cleaning strategies which can be costly. Optimized cleaning strategies have provided where a balance between costs and economic losses can be used to give fixed cleaning strategies. However, looking at the dynamics of dust deposition, cost of cleaning and performance restoration after cleaning, we believed that a solution exists where we can have an optimal cleaning strategy with a variable cleaning strategies. Our optimal solution will offer variability in the time to clean and the number of solar panels that can be cleaned thereby reducing the cleaning cost whilst maintaining the plants' power generation capacity.

CHAPTER 4 OPTIMAL CLEANING STRATEGY

In this chapter, an optimal cleaning strategy is developed for large scale solar photovoltaic plants using mathematical models, as a solution to the effects of non-uniform dust deposition on large scale PV plants. The optimal strategy is developed in three parts:

1. In the first part, mathematical modeling of a PV array is done.
2. In the second part, effect of dust deposition and more so non-uniform dust deposition is presented. Two scenarios are presented to illustrate and explain non-uniformity of dust deposition. The Monte Carlo simulation is used to generate the non-uniformity pattern.
3. The final part details the formulation of the optimal cleaning model.

The resulting optimal cleaning model is then applied to a case study and the observations given.

4.1 MATHEMATICAL MODELING FOR THE OPTIMAL CLEANING STRATEGY

4.1.1 Solar photovoltaic array modeling

To model the solar array, the single diode PV cell model is used. The components of the model include a photocell, one diode, one series resistance and one shunt resistance. Using these components, the following equations are defined.

The current output of the PV cell is given by Equation (4.1) [36]:

$$I = I_L - I_d - I_{sh}, \tag{4.1}$$

where I_L is the light-generated current or photo-current in Amps, I_d is the diode current in Amps, and I_{sh} is the shunt current in Amps. The light-generated I_L is given by Equation (4.2) [36]:

$$I_L = \frac{G}{G_r}(I_{scc} + k_i(T_c - T_{c,ref})), \tag{4.2}$$

where G and G_r are the real-time and reference solar irradiances respectively in W/m^2, I_{scc} is the short-circuit current in Amps at Standard Test Conditions (STC). T_c and $T_{c,ref}$ are the real-time and reference solar PV cell temperatures, respectively in Kelvin (K), and k_i is the current temperature coefficient in A/K. The diode current I_d, is given by Equation (4.3) [36]:

$$I_d = I_{os}\left[\exp\left(q\left(\frac{V+IR_s}{AkT_c}\right)\right) - 1\right], \tag{4.3}$$

where I_{os} is the saturation current, q is the electron charge in eV, V is the DC output voltage in volts, I is the output current in Amps, R_s is the series resistance in Ohms, A is the diode ideality factor and k is the Boltzmann constant. I_{os} has a strong dependence on solar cell temperature and can be expressed as in Equation (4.4) [36]:

$$I_{os} = I_{os-ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left(\frac{qE_g}{Ak}\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right). \tag{4.4}$$

The shunt current I_{sh} is given by Equation (4.5) [36]:

$$I_{sh} = \frac{V+IR_s}{R_{sh}}, \tag{4.5}$$

where R_s is the resistance connected in series, R_{sh} is the shunt resistance. Using Equations (4.3), (4.5) and Equation (4.1), the solar panel output current becomes [36]:

$$I = I_{pv} - I_o\left[\exp\left(\frac{V+IR_s}{AV_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}}, \tag{4.6}$$

where V_T is given by:

$$V_T = \frac{kT_c}{q}. \tag{4.7}$$

For a large PV array with N_{ss} series and N_{pp} parallel connected solar panels, Equation (4.6) becomes [36]:

$$I = I_{pv}N_{pp} - I_oN_{pp}\left(\exp\left(\frac{V+IR_s\frac{N_{ss}}{N_{pp}}}{AV_TN_{ss}}\right) - 1\right) - \frac{V+IR_s\frac{N_{ss}}{N_{pp}}}{R_{sh}\left(\frac{N_{ss}}{N_{pp}}\right)}. \tag{4.8}$$

4.1.2 Dust deposition on solar panels

Factors that influence the dust deposition include the tilt angle (β in $^\circ$), exposure period, and environmental factors such as wind and rainfall [5]. The dust deposition density on a solar panel reduces as the tilt angle β increases. Dust deposition measurements are mostly taken on horizontal surfaces where β=0°, therefore we assume that the dust deposition density ρ_D at β = 0°, can be measured and given as a value ρ_{D0}. As β changes, the dust deposition density (ρ_D) also changes.

A detailed review of previous dust deposition models was done to find a suitable model for this study. A model developed by [5] in a study in Minia, Egypt was selected to use in modeling the dust deposition. The model was found to be robust as data was collected over a long period without cleaning, covering different weather seasons. To develop the model, data was collected using exposed glass plates over one year. The data collection period covered two main weather seasons: summer in May to October and winter in December to February. Transmittance through the plates was measured for different tilt angles and days of exposure. The study described a factor known as the transmittance dust factor given by:

$$F_d = \frac{\tau}{\tau_{clean}}, \tag{4.9}$$

where τ is the transmittance of a dusty solar panel and $\tau_c lean$ is the transmittance of a clean solar panel. A graph of the transmittance reduction factor vs the dust deposition density for various tilt angles of glass samples was plotted. Using non-linear regression, a mathematical correlation was obtained, describing the relationship between transmittance reduction and dust deposition.

Other dust deposition models in past studies include a 4$^{\text{th}}$ polynomial mathematical model that showed the correlation between transmittance reduction and dust deposition [20]. The model was developed after a seven months' outdoors study where samples were set at different tilt angles. A plot of the transmittance reduction vs dust deposition showed an increase in transmittance reduction until a point of stagnation. This model involved a shorter measurement period as compared to [5] hence note selected for thus study. Another model was developed after an experiment involving 2 solar panels tilted at 30ř [81]. Dust particles were sprayed on the solar panels using a fan and measurements taken. A plot of the measured efficiency against dust deposition was done and a linear mathematical model realized for dust deposition below 1.5 g/m^2. The model relied on experimental setup and its data was collected over short period of time, hence not ideal for this study.

The linear relationship between ρ_D and β is given by Equation (4.10) [82]:

$$\rho_D(\beta) = -8.5 \times 10^{-3} \rho_{D0} \beta + 0.82 \rho_{D0}, \tag{4.10}$$

where $\rho_D(\beta)$ is function of the dust deposition density on a solar panel at a tilt angle of β and ρ_{D0} is the dust deposition density at the horizontal position (β=0°). Dust deposition reduces the irradiance reaching the PV cells, a process known a transmittance reduction. The relationship between transmittance reduction and dust deposition density can be described by Equation (4.11) [5]:

$$\left(1-\frac{\tau}{\tau_{clean}}\right)\% = 34.37\,\mathrm{erf}\left(0.17{\rho_D}^{0.8473}\right), \tag{4.11}$$

where τ is the transmittance of the dusty solar panels, τ_{clean} is the transmittance of the clean solar panels and erf is the Gauss error function. τ can then be given by Equation 4.12 [5]:

$$\tau = \tau_{clean}\left\{1-0.3437\,\mathrm{erf}\left(0.17{\rho_D}^{0.8473}\right)\right\}. \tag{4.12}$$

Equation (4.10) and Equation (4.12) give:

$$\tau = \tau_{clean}\left\{1-0.3437\,\mathrm{erf}\left(0.17\left(-8.5\times 10^{-3}\rho_{D0}\beta+0.82\rho_{D0}\right)^{0.8473}\right)\right\}. \tag{4.13}$$

$\tau = \tau_{clean}$ when dust deposition $\rho_{D0} = 0$. The irradiance that reaches the PV cells in the presence of dust deposition on a solar panel is therefore penalized by the factor τ, such that:

$$G_{dusty} = G_{clean} \times \tau, \tag{4.14}$$

where G_{dusty} is the irradiance through a dusty solar panel and G_{clean} is the irradiance through a clean solar panel. The new irradiance G_{dusty} due to dust deposition is then substituted in Equation (4.2) to obtain the current output.

4.1.3 Non-Uniformity of dust deposition on solar panels

When dust deposits on the surfaces of solar panels in a PV array, the spread of dust on the surface can be said to be uniform or non-uniform. For a given solar PV array, the dust deposition density is said to be uniform when following conditions are satisfied:

1. The solar panels are identical in terms of technical specifications, age, and degradation conditions, and tilt angle;
2. The dust deposition density on each solar panel are the same;
3. Dust deposition on individual solar panels is evenly distributed; and
4. The solar panels are working under a uniform irradiance condition.

Practically, it is unlikely that the dust deposition densities on the solar panels are uniform. Instead, the dust deposition densities are non-uniform, even for an individual solar panel. The way the dust deposition spreads non-uniformly on the solar panel can be described by non-uniformity dust deposition patterns. One non-uniformity dust deposition pattern is when dust gathers at the edges of solar panels while the other parts have a lot less dust deposition, as seen in photographs in [8]. In the same study, non-uniform dust deposition patterns were brought about by dust settling on the lower parts of tilted solar panels. Non-uniformity dust deposition patterns can also form when scanty rain falls on dusty solar panels forming mud streaks as the rain water mixes with dust and runs down the surface of the solar panels [6]. Non-uniformity patterns can therefore be said to arise from many situations and can be quite complex to categorize. We have therefore brought forth a simplified description and categorization of non-uniformity of dust deposition. The categorization describes non-uniformity in 3 different ways:

1. with the PV cell being the minimum unit, meaning that dust deposition varies from one PV cell to another PV cell;
2. with the solar panel being the minimum unit meaning that dust deposition on one solar panel is less or more than the dust deposition on another solar panel;
3. with the PV array being the minimum unit meaning that dust deposition on one PV array is less or more than the dust deposition on another PV array.

In this study, non-uniformity is explained with the solar panel being the minimum unit.

The amount of dust deposition on the solar panels can be defined by τ in Equation 4.14 as a ratio of the irradiance of a dusty solar panel and the the irradiance of a clean solar panel. The ratio is converted to percentage varying from 0% to 100%. To illustrate the effects of dust deposition, Figure 4.1 shows a solar array with values of shading percentages given by $1-\tau$, such that 0% indicates a clean solar panel, while 100% indicates a heavily dusty one. Dust deposition on each solar panel negatively affects the transmittance of the affected solar panels, with the solar panel having the highest shading percentage being the most affected. From Figure 4.1, we notice that one PV string can have solar panels with different shading percentages. Current from the PV string is therefore limited by the current from the un-bypassed solar panel with the heaviest shading. For a PV string made up of n solar panels, the output current and output voltage from the PV string are given by Equations (4.15) and (4.16) [83]:

$$I_s = min(I_{m1}, I_{m2}, I_{m3}, ..., I_{mn}), \tag{4.15}$$

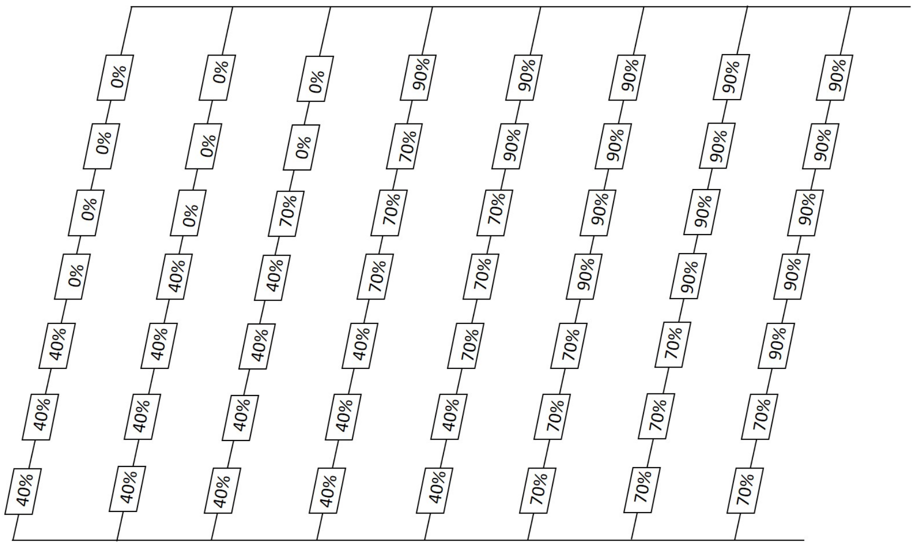


Figure 4.1. Non-uniform dust deposition on a PV array

where I_s is the current from the string and $I_{m1}, I_{m2}, I_{m3}, ..., I_{mn}$ are output currents from solar panels $1, 2, 3, ..., n$. The output voltage from each string is given by:

$$V_s = \sum_{i=1}^{n} V_{mn}, \tag{4.16}$$

where V_s is the voltage output from the PV string, V_m is the output voltage from solar panels 1 to n in the PV string. For the PV array in Figure 4.1, the power from the PV array is then given as:

$$P_{array} = \sum_{s=1}^{n} P_s, \tag{4.17}$$

where P_{array} is the power generated by the PV array, P_s is the power output from PV string 1 to PV string S in the PV array. To further explain non-uniformity of dust deposition and its effects, two scenarios are considered in the subsections that follow. The first scenario is when there is non-uniformity on a PV array that has equally rated solar panels. The second scenario is when there is non-uniformity on a PV array that has unequally rated solar panels.

4.1.3.1 Non-uniformity of dust deposition with equally rated solar panels

In such a scenario, all solar panels in the PV array have the same technical specifications. The maximum ratings of all solar panels in a clean state are $350.39\,W_p$, $6.302\,A$ and $55.6\,V$. Non-uniformity in this scenario means that the solar panels in a PV string have different levels of dust deposition and shading percentages. In Figure 4.1, consider the first string, 'String 1', with solar panels $M1$, $M2$, $M3$ and $M4$. Using the model in Section 4.1.1, the I-V and PV curves are obtained using Equation (4.17). The first result is given for when there is no shading for all the solar panels (0% shading). The maximum current, voltage and power from each PV string remains as was in the clean state. The total array output becomes $4204.73\,W$. The second results are for when shading due to non-uniform dust deposition occurs as in Figure 4.1. The shading percentages of the solar panels are 10% for $M1$, 10% for $M2$, 0% for $M3$ and 0% for $M4$. It is observed that the maximum current, voltage and power for each string reduces as shown in Table4.1. The higher the shading percentage, the lower the current from the solar panel and PV string. PV string 2 has the solar panel with the highest shading percentage of 70% and gives a string current output of $2.873A$, even though solar panel $M4$ in the same PV string has a lower shading percentage of 10% and higher current of $5.677A$. Non-uniform dust deposition therefore causes a negative effect on the PV string current.

4.1.3.2 Non-uniformity of dust deposition with unequally rated solar panels

In such a scenario, a PV array has solar panels with different technical specifications. String 1 and 3 have solar panels rated $173.47\,W_p$, $7.289\,A$ and $23.8\,V$ while string 2 has 2 solar panels rated $173.47\,W_p$ and 2 solar panels rated $350.39\,W_p$, $6.302\,A$ and $55.6\,V$. When there is no dust deposition, maximum ratings apply and the power generated by the PV array is $2,388.5\,W$. With non-uniformity, the output characteristics are as given in Table 4.2. From Figure 4.2, the PV array power output with no shading is $2,435.4\,W$. PV string parameters are also as shown in Table 4.2. PV string 2 has solar panels with unequal ratings and this is seen to lower the PV string current to the value of the lowest rated solar panel. When shading happens as in Figure 4.1, the output current of PV string 2 is further affected as it drops to $2.146\,A$. The power output from the PV array also reduces from the maximum $2,435.4\,W$ to $1,136.74\,W$. It is concluded therefore that mixing unequally rated solar panels in one PV string limits the current from the PV string to the lowest generated current. In addition, adding non-uniformity to it further reduces the current per PV string hence leading to even lower current and power output.

To reduce significant power loss, bypass diodes are used in solar panels to enable current to flow around shaded PV cells in solar panels. The bypass diodes however cause multiple maximum peaks to form in the I-V and P-V curves of solar panels and arrays. The peaks formed include low peaks known as local maximum power points (LMPP) and one highest peak known as the global maximum power point (GMPP). At these peaks, I = I_{mp} and $V = V_{mp}$ and the derivative of power with voltage is equal

Table 4.1. Non-uniformity on solar panels with equal wattages

		No shading				**With shading**			
		Shading percentage (%)	**Max current (A)**	**Max voltage (V)**	**Max power (W)**	**Shading percentage (%)**	**Max current (A)**	**Max voltage (V)**	**Max power (W)**
String 1	M 1	0%	6.302	55.6	350.39	10%	5.677	55.3	313.92
	M 2	0%	6.302	55.6	350.39	10%	5.677	55.3	313.92
	M 3	0%	6.302	55.6	350.39	0%	6.302	55.6	350.39
	M 4	0%	6.302	55.6	350.39	0%	6.302	55.6	350.39
String 1 total			**6.302**	**222.4**	**1401.57**		**5.677**	**221.8**	**1259.16**
String 2	M 1	0%	6.302	55.6	350.39	70%	2.873	21.3	61.19
	M 2	0%	6.302	55.6	350.39	70%	2.873	21.3	61.19
	M 3	0%	6.302	55.6	350.39	40%	5.080	22.8	115.8
	M 4	0%	6.302	55.6	350.39	40%	5.080	22.8	115.8
String 2 total			**6.302**	**222.4**	**1401.57**		**2.873**	**221.8**	**1259.16**
String 3	M 1	0%	6.302	55.6	350.39	70%	2.516	53.5	134.6
	M 2	0%	6.302	55.6	350.39	0%	6.302	55.6	350.39
	M 3	0%	6.302	55.6	350.39	70%	2.516	53.5	134.6
	M 4	0%	6.302	55.6	350.39	0%	6.302	55.6	350.39
String 3 total			**6.302**	**222.4**	**1401.57**		**2.516**	**221.8**	**1259.16**
Array					**4,204.71**				**2,061.58**

to zero when, that is:

$$\frac{dP}{dV} = 0. \tag{4.18}$$

Due to the multiple power peaks, maximum power point trackers can pick a LMPP as it is still a maximum power point thereby resulting in low power output. Extraction of the GMPP is therefore necessary. The GMPP extracted is then used in optimization of the cleaning strategy.

Table 4.2. Non-uniformity on solar panels with unequal wattages

		No shading				With shading			
		Shading percentage (%)	Max current (A)	Max voltage (V)	Max power (W)	Shading percentage (%)	Max current (A)	Max voltage (V)	Max power (W)
String 1	M 1	0%	7.288	23.8	173.47	10%	6.552	23.5	153.98
	M 2	0%	7.288	23.8	173.47	10%	6.552	23.5	153.98
	M 3	0%	7.288	23.8	173.47	0%	7.288	23.8	173.47
	M 4	0%	7.288	23.8	173.47	0%	7.288	23.8	173.47
String 1 total			**7.288**	**95.2**	**693.82**		**6.552**	**94.6**	**619.82**
String 2	M 1	0%	6.302	55.6	350.39	70%	2.146	20.5	43.98
	M 2	0%	6.302	55.6	350.39	70%	2.146	20.5	43.98
	M 3	0%	7.288	23.8	173.47	40%	4.407	54.8	241.50
	M 4	0%	7.288	23.8	173.47	10%	6.553	23.5	153.99
String 2 total			**6.302**	**158.8**	**1000.76**		**2.146**	**119.3**	**256.02**
String 3	M 1	0%	7.288	23.8	173.47	70%	2.146	20.5	43.98
	M 2	0%	7.288	23.8	173.47	0%	7.288	23.8	173.47
	M 3	0%	7.288	23.8	173.47	70%	2.146	20.5	43.98
	M 4	0%	7.288	23.8	173.47	0%	7.288	23.8	173.47
String 3 total			**7.288**	**95.2**	**693.82**		**6.552**	**94.6**	**619.82**
Array					**2,435.40**				**1,136.74**

4.1.4 Solar panel cleaning optimization

In this subsection, the mathematical model to carry out optimal cleaning of solar panels is formulated. In this study, our goal is to identify the optimal cleaning strategy for large scale solar power plants that are prone to dust deposition. The main priority of the study is to achieve a cost effective cleaning strategy. We therefore formulate the solar panel cleaning problem as a constrained optimisation problem. The objective function is formulated as a cost function denoting the net benefit from cleaning the solar panels. The net benefit is defined as the difference between the income from the additional power generation due to cleaning and the cleaning cost of solar panels. The decision variables are the number of PV strings of solar panels to be cleaned at each cleaning interval. To carry out cleaning, a solar PV cleaning machine is used. The solar PV cleaning machine uses brushes, water and soap. The machine is placed on one end of the PV string and moved across it to clean before it is relocated to clean the next PV string. After cleaning, the solar panel generated the original power output.

This study aims to maximize the additional revenue generated due to cleaning and is expressed as:

$$J = \sum_{k=1}^{K} \sum_{s=1}^{S} \left(R_s(k) - \overline{R}_s(k) \right), \tag{4.19}$$

where $R_s(k)$ is the revenue generated from a cleaned PV string and $\overline{R}_s(k)$ is the revenue generated from a dusty PV string, S is the total number of PV strings at any index of time interval, s is the index of PV strings such that $s = 1, 2, \ldots, S$, K is the number of time intervals and k is the index of time intervals such that $k = 1, 2, \ldots, K$. The net revenue generated from a clean PV string at any time k is the difference between the sales and the cleaning cost at the time k, such that:

$$R_s(k) = P_s(u_s(k))h(k)f(k) - C_s u_s(k), \tag{4.20}$$

where $P_s(u_s(k))$ is the power generated from a PV string at time k. $u_s(k)$ is the binary decision variable that defines whether or not to clean a PV string s at time k,

$$u_s(k) \in \{0, 1\} \text{ for } 1 \leq k \leq K, \tag{4.21}$$

where $u_s(k) = 0$ indicates no cleaning and $u_s(k) = 1$ indicates cleaning of PV string s at time k. $h(k)$ is the peak sun hours and $f(k)$ is the electricity tariff. C_s is the cost to clean of a PV string. For a dusty PV string, the revenue generated is determined by the electricity sales made from dusty solar panels without being cleaned, and

$$\overline{R}_s(k) = \overline{P}_s(u_s(k))h(k)f(k), \tag{4.22}$$

where $\overline{P}_s(u_s(k))$ is the power generated from a dusty PV string at any time k.

The optimization problem in Equation 4.19 is subject to the following constraints.

1. The total number of PV strings to be cleaned at each time period should be between the minimum and the maximum number of PV strings at the PV plant, that is:

$$0 \leq \sum_{s=1}^{S} u_s(k) \leq S. \tag{4.23}$$

2. The power generated from each PV string should be within the boundary of the minimum and maximum power levels set by the power plant, hence:

$$P_s^{min}(k) \leq P_s(k) \leq P_s^{max}(k), \tag{4.24}$$

where $P_s^{min}(k)$ and $P_s^{max}(k)$ are the minimum and maximum solar power generation levels.

4.1.5 Optimization algorithm

The optimisation problem in Eqs. (4.19) - (4.24) is an integer linear programming problem, which can be solved using the "intlinprog" function in the Optimization Toolbox in MATLAB [84]. The objective function is formulated in the form:

$$maximize_u \quad f(u), \tag{4.25}$$

$$subject\,to \quad lb \leq u \leq ub, \tag{4.26}$$

$$Au \leq b, \tag{4.27}$$

$$u \in \{0,1\}. \tag{4.28}$$

$f(u)$ is the objective function and in this study it is expressed as:

$$f(u_s(k)) \quad = \quad \begin{bmatrix} \left(R_1(k) - \overline{R}_1(k)\right) & \left(R_2(k) - \overline{R}_2(k)\right) & \dots & \left(R_S(k) - \overline{R}_S(k)\right) \end{bmatrix}_{1\times S}. \tag{4.29}$$

The linear inequality is expressed as:

$$A(k)u_s(k) \leq b(k), \tag{4.30}$$

where:

$$A(k) = \begin{bmatrix} P_1(k) & 0 & \dots & 0 \\ 0 & P_2(k) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & P_S(k) \end{bmatrix}_{S\times S}, \tag{4.31}$$

and

$$b(k) = \begin{bmatrix} P_1^{min}(k) \\ P_2^{min}(k) \\ \vdots \\ P_S^{min}(k) \end{bmatrix}_{S\times 1}. \tag{4.32}$$

The decision variable for this optimization problem, is written in the form:

$$u(k) = \begin{bmatrix} u_1(k) & u_2(k) & \dots & u_S(k) \end{bmatrix}^T_{S\times 1}. \quad (4.33)$$

4.2 CASE STUDY

To illustrate the effectiveness of the proposed solar panel cleaning optimisation model, a case study is presented in this section.

4.2.1 Background

An installed solar PV plant in South Africa consists of 100 polycrystalline solar panels. The 100 solar panels form a 10×10 PV array with 10 PV strings each having 10 solar panels. Technical specifications of the solar panels are given in Table 4.3. The specifications are used as initial values for mathematical simulation and are obtained from [85] except for E_g, K and q which were obtained from [86]. Presented in Table 4.4, are solar irradiance records [87] and dust deposition records [88] for location of the solar PV plant between 2012 and 2013..

Table 4.3. Solar panels specifications

Parameter	Value	Parameter	Value
PV type	Polycrystalline	R_s	0.394 Ω
Cells connection	Series	R_{sh}	884.55 Ω
Number of cells	96	T_{NOCT}	47.5°C
V_{mp}	57.3 V	k_i	0.07
I_{mp}	6.02 A	k_v	-0.356
P_{mp}	344.95 W	E_g	1.12
V_{oc}	68.2 V	K	1.38×10^{-23}
I_{sc}	6.39 A	q	1.607×10^{-19}

The solar plant has a goal of maintaining the power levels above a minimum capacity of 80% of its original output. Cleaning of the solar panels is done once every month in an effort to maintain the power level. Regular cleaning cost of the solar panels includes labour cost and water consumption.

Table 4.4. Solar irradiance and dust deposition records.

Month	**Solar irradiance (W/m^2)**	**Dust deposition (g/m^2)**
January	1001.94	1.50
February	962.59	1.40
March	896.08	1.65
April	795.79	1.80
May	736.88	2.20
June	652.95	1.48
July	768.68	1.51
August	752.57	1.50
September	848.45	1.63
October	932.23	1.62
November	976.35	1.01
December	994.95	0.61

The labour cost is R 20[1] per hour. Cleaning of one PV string requires 9.8 litres of water by R 6 per litre. The solar power plant's feed-in tariff to the grid is R 0.79/kWh [89].

4.2.2 Simulation setup

As introduced in Section 4.2.1, the solar plant cleans all the solar panels once every month and all solar panels are cleaned during each cleaning action. The cleaning efforts are effective; however they may not be cost-effective. The plant owners are keen on a optimized cleaning strategy. Using modeling and dust deposition characteristics of solar panels, and the relationships between power generation and the dust deposition, a constrained optimisation problem is formulated in Section 4.1. To solve this optimisation problem, we look into an optimal cleaning strategy over a calendar year with a sampling interval of a month.

Using "intlinprog" function in MATLAB's Optimization Toolbox, the optimization problem can be solved with the optimisation settings shown in Table 4.5, where the dual-simplex algorithm is selected

[1] 1 U.S. dollar ($) = 14.28 South African Rand (R)

Table 4.5. Optimization settings.

Category	**Options**
Algorithm	dual-simplex
TolCon	10^{-6}
TolX	10^{-5}
Max nodes	10000000
Max time	7200 s
lb: $(u_1(k), u_2(k), \dots u_S(k))$	$(0, 0, \dots, 0)$
ub: $(u_1(k), u_2(k), \dots u_S(k))$	$(1, 1, \dots, 1)$
u_0: $(u_1(k), u_2(k), \dots u_S(k))$	$(0, 0, \dots, 0)$

as the optimization algorithm; maximum nodes and the maximum time are given in addition to the tolerances of the function value and constraint. A searching starting point u_0 and the bounds of the decision variables are also given.

To highlight the advantageous performance of the proposed optimal solar panel cleaning model, we also analysed performances of other solar panel cleaning approaches, namely:

i) **Full cleaning:** refers to the case when all the PV strings are cleaned at every time interval.
ii) **No cleaning:** no solar panel is cleaned over the entire evaluation period.
iii) **Random cleaning:** refers to 1) clean random number of PV strings at optimal cleaning strategies; 2) clean optimised number of PV strings at random cleaning strategies; and 3) clean random numbers of PV strings at random cleaning strategies.

4.3 OPTIMIZATION RESULTS AND DISCUSSION

The I-V characteristics (blue curve) and P-V characteristics (red curve) of the clean PV array are shown in Figure 4.2. Both curves have a single peak where the maximum current is 67.10 A, the maximum voltage is 547.00 V and the maximum power is 34.83 kW. As time goes by, non-uniform dust deposition starts to occurs. Non-uniform dust deposition patterns form on the solar panels. To generate these patterns, Monte Carlo simulation is used. The non-uniformity dust deposition patterns

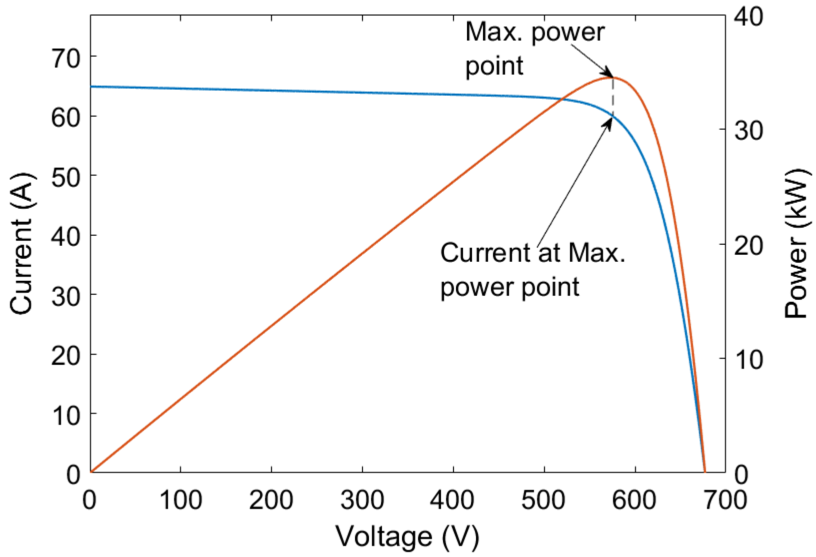


Figure 4.2. Clean solar panels

simulated for the month of (February and June) are shown in Figures 4.3 and 4.4. In February, dust deposition is less compared to the dust deposition in June. The reason is that in at the beginning of January, all the solar panels are new and clean. The non-uniformity dust deposition pattern for February is shown in Figure 4.3. Since no cleaning is done, dust deposition continues to occur and by June, the non-uniform dust deposition pattern is as in Figure 4.4. After obtaining the non-uniformity patterns, the corresponding I-V and P-V characteristics can be obtained as shown in Figures 4.5 and 4.6 .

In Figure 4.5, the P-V curve shows one peak which is more pronounced than others which are quite subtle. The maximum power peak is at 29.67 kW, maximum current of 51.92 A and maximum voltage of 571.95 V. This peak is known as the global maximum power point (GMPP). The rest of the peaks are quite subtle and are referred to as the local maximum power points (LMPP) as they are lower than the global peak. Peaks are brought about by different shading profiles on the solar panels along the PV strings. The danger of having multiple peaks is that the MPP tracker can pick the LMPP instead of the GMPP since they all appear to be maximum power points. A comparison of the results obtained for the non-uniformly dirty solar panels in February and June, to the results of clean solar panels is given in Table 4.6. From the comparison, the maximum current and maximum power are seen to reduce more than the maximum voltage in February. A more significant reduction is observed in June for the maximum current and maximum power. The maximum voltage in June still has a small reduction. The

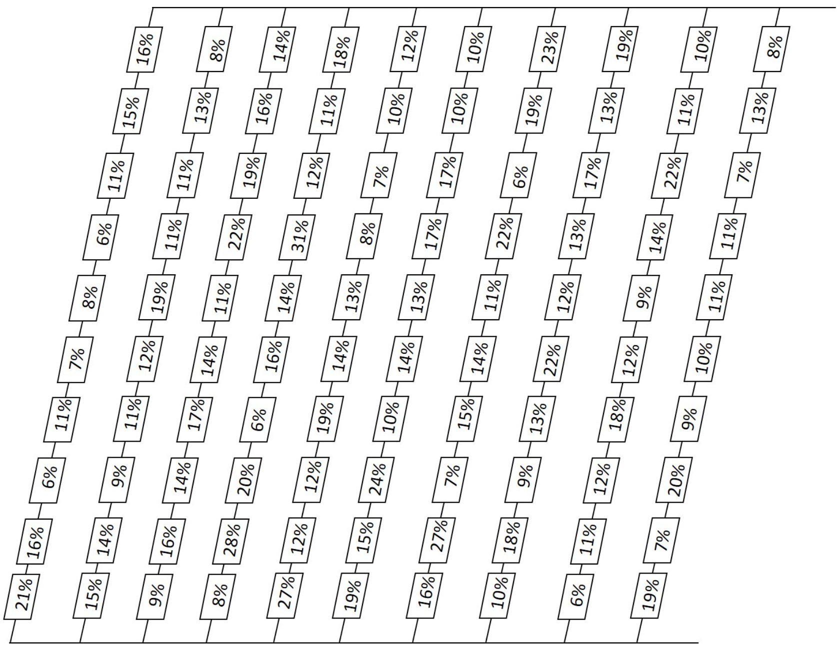


Figure 4.3. Non-uniformity pattern for February

largest contributor to the reduction in the maximum power is therefore seen to be the output current.

Table 4.6. Comparison of clean and non-uniformity in February and June

	Clean condition	**February**	**June**
Max. current (A)	60.20	51.92	35.84
Max. voltage (V)	572.98	571.95	533.22
Max. power (kW)	34.49	29.67	19.12

In both February and June, it is observed that non-uniform dust deposition causes reductions in both the maximum current and power output. The maximum current reduces significantly causing the maximum power to reduce significantly. The changes in voltage are however relatively small. Maximum current is therefore the major contributor to loss in the maximum power output.

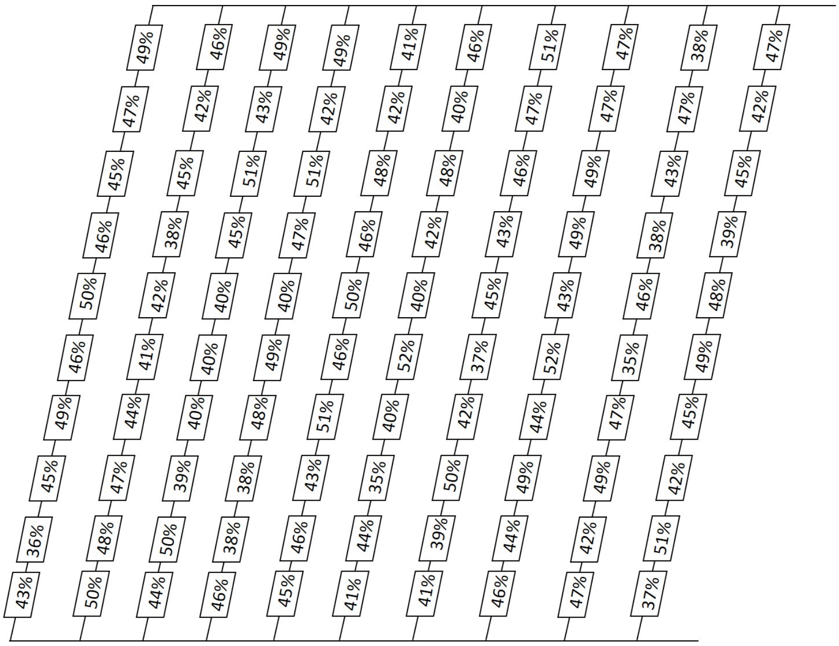


Figure 4.4. Non-uniformity pattern in June

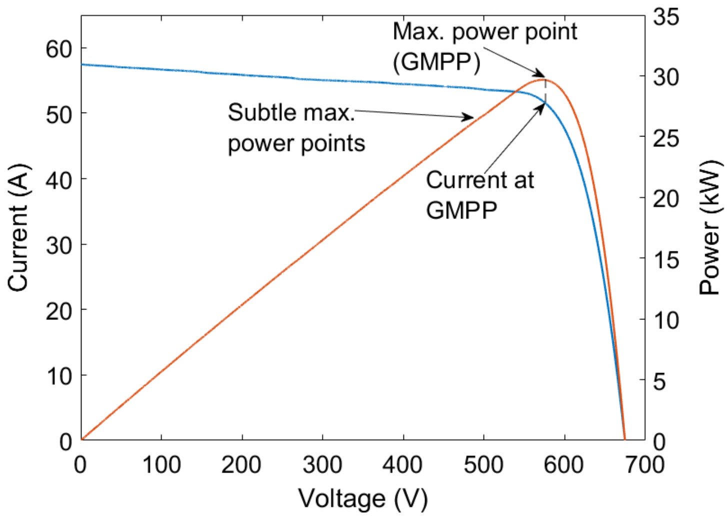


Figure 4.5. I-V and P-V characteristics in February

4.3.1 Cleaning strategies

Considering the effect of non-uniform dust deposition on the power output, cleaning strategies are developed. Four different scenarios are considered as outlined in the simulation setup. Results of the scenarios are given as follows:

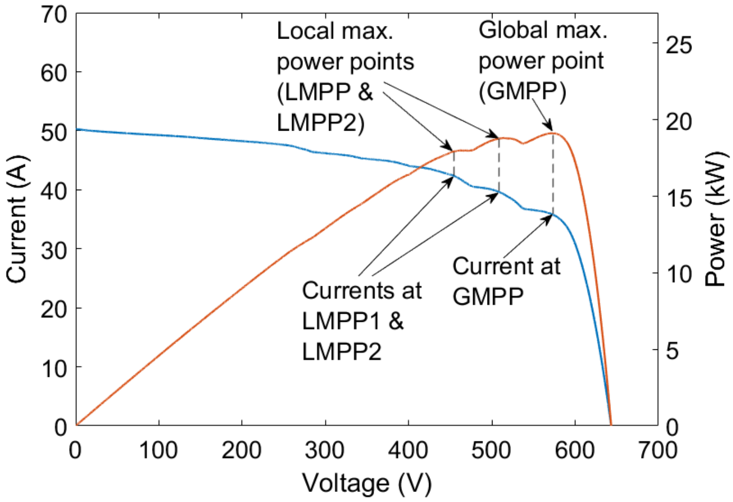


Figure 4.6. I-V and P-V characteristics in June

4.3.1.1 Scenario 1: Optimal cleaning strategy

The optimal solar panel cleaning strategy in terms of number of PV strings to be cleaned at each time interval is given graphically in Figure 4.7 and numerically in Table 4.9. Optimal cleaning is done at 7 time instants $t = 2,3,6,7,10,11$, and 12, over the evaluation period. The total number of PV strings cleaned is 24 giving a total cleaning cost of R $1,440$. The dynamics of the power output due to the optimized cleaning strategy are given in Figure 4.7. From the figure, the power output at the start of the evaluation period is 28.57 kW. As time goes by, dust continues to accumulate on solar panels causing a reduction in the PV power generated. In order to avoid the total generation capacity dropping below the minimum power generation threshold, the first cleaning is advised by the optimisation algorithm at t=2 for PV strings 3, 6 and 7. After the first cleaning at $t = 2$, the power level goes from 23.93 kW to 24.46 kW. Had there been no cleaning, the power would have reduced to 22.50 kW as shown by the the 'no cleaning' curve in Figure 4.7. Another factor that contributes to the change in power level is the solar irradiance. As can be observed from Figure 4.7, solar power generation varies even with full cleaning strategy implemented. This is mainly caused by the changes in the solar irradiance. In South Africa, January is summer time with high levels of solar irradiance while June is the winter time with relatively low levels of solar irradiance. The reduced solar irradiance results in a slight reduction in the power output even though cleaning has been done.

At t=3, a second solar panel cleaning action is triggered for the PV strings $1,2,4,5,8,9$ and 10, which

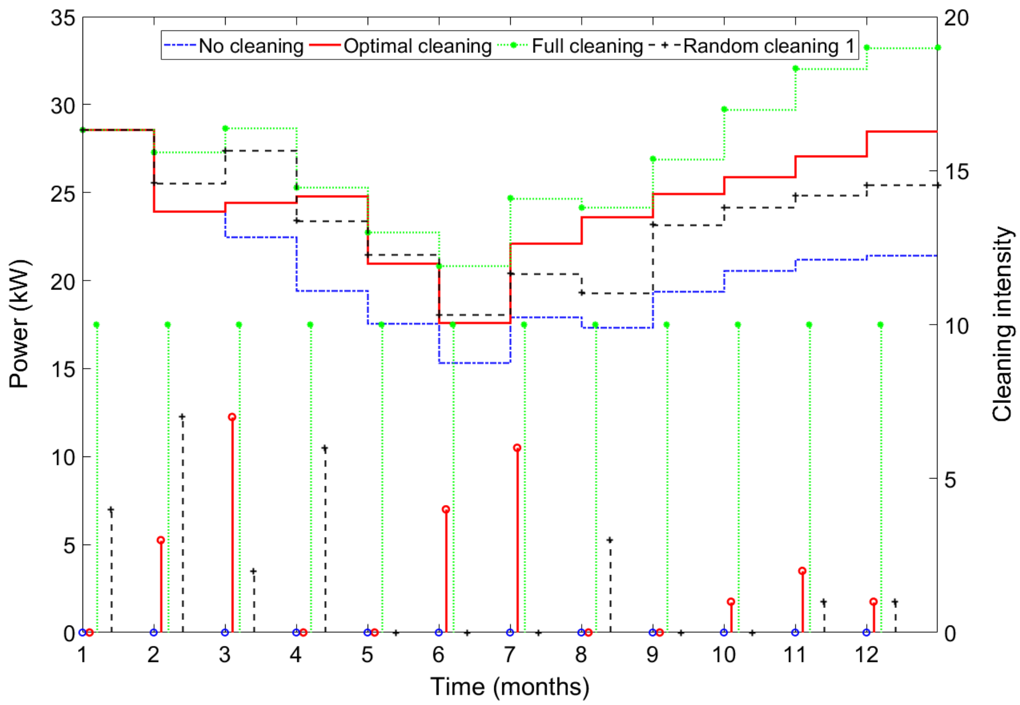


Figure 4.7. Optimal cleaning strategy

are the solar panels with high level of dust deposition that generate the least amount of power output. Changes in the PV array power generation are shown in Table 4.7. The power goes from 24.46 kW to 24.82 kW. The 'no cleaning' curve shows a more obvious decrease had the PV string not been cleaned. By t=6, another cleaning action is triggered and 4 PV strings are cleaned as shown in Figure 4.7, increasing the power output for the array to 22.10 kW. The total power and energy generated throughout the evaluation period are 292.48 kW and 35,318 kWh. The associated cleaning cost is R 1,440 which gives net sales of R 26,461.

4.3.1.2 Scenario 2: Full cleaning strategy

Without considering optimisation, some solar power plants may decide to carry out cleaning of all solar panels on monthly basis. In this case, the cleaning cost is incurred at every time interval, which totals a cost of R 7,200. Although cleaning of all solar panels is done, fluctuating irradiance still affects the power output. Lowest irradiance occurs in the middle of the year as opposed to the start or the end of the year resulting in the trend of the power output shown in Figure 4.7. A full cleaning strategy does ensure the maximum solar power generation, which is however not the most beneficial approach due

Table 4.7. Solar power generation (kW) with optimal cleaning.

	March	June	October
String 1	2.299	1.778	2.564
String 2	2.300	1.796	2.568
String 3	2.590	1.706	2.460
String 4	2.230	1.788	2.576
String 5	2.282	1.771	2.548
String 6	2.596	1.676	2.406
String 7	2.591	1.693	2.435
String 8	2.265	1.765	2.541
String 9	2.232	1.758	2.438
String 10	2.294	1.776	2.550

Table 4.8. Comparison of various cleaning strategies.

	Optimal cleaning	Full cleaning	No cleaning	Random cleaning 1	Random cleaning 2	Random cleaning 3
No. of cleaned PV strings	24	120	0	39	24	42
No. of cleaning intervals	7	12	0	12	7	8
Cleaning cost (R)	1,440	7,200	0	2,340	1,440	2,520
Electricity generated (kWh)	35,318	39,935	30,007	35,440	34,600	36,009
Electricity sales (R)	27,901	31,549	23,706	27,998	27,334	28,447
Net sales (R)	26,461	24,349	23,706	25,658	25,894	25,927

to the extra cleaning cost. Detailed cost analysis for the full cleaning strategy is shown in Table 4.8. Graphical comparison of the optimal and full cleaning strategy is given in Figure 4.8.

4.3.1.3 Scenario 3: No cleaning strategy

When the dusty solar panels are not cleaned, the power generation of the solar PV array reduces continuously and significantly as shown in Figure 4.7. The analysis for the 'no cleaning' strategy clearly demonstrates the negative impact of non-uniform dust deposition on the solar panels. The net

Table 4.9. PV strings to be cleaned over the evaluation period.

Month	Optimal cleaning	Full cleaning	No cleaning	Random cleaning 1	Random cleaning 2	Random cleaning 3
January	-	1,2,3,4,5,6,7,8,9,10	-	-	3,6,7,9	1,3,6,7,8,9
February	3,6,7	1,2,3,4,5,6,7,8,9,10	-	1,2,4,5,8,9,10	1,2,4,5,8,9,10	1,2,3,4,5,7,9
March	1,2,4,5,8,9,10	1,2,3,4,5,6,7,8,9,10	-	2,3,5,8,9,10	7,9	-
April	-	1,2,3,4,5,6,7,8,9,10	-	-	1,2,4,5,8,10	4,5,7
May	-	1,2,3,4,5,6,7,8,9,10	-	-	-	1,2,6,7,8,10
June	3,6,7,9	1,2,3,4,5,6,7,8,9,10	-	1,3,4,5,6,7,9	-	-
July	1,2,4,5,8,10	1,2,3,4,5,6,7,8,9,10	-	1,6,7,9	-	-
August	-	1,2,3,4,5,6,7,8,9,10	-	-	3,6,7	1,5,7,9
September	-	1,2,3,4,5,6,7,8,9,10	-	-	-	1,2,3,4,5,9
October	6	1,2,3,4,5,6,7,8,9,10	-	3,4,8,9,10	-	1,3,7,10
November	7,9	1,2,3,4,5,6,7,8,9,10	-	2,3,7,9	3	-
December	3	1,2,3,4,5,6,7,8,9,10	-	1,3,4,5,6,7	6	1,2,3,5,6,8

sales are R $23,706$, which is the worst of all cleaning strategies considered, as shown in Table 4.8. The power and financial analysis for the no cleaning strategy clearly demonstrates the negative effects of non-uniform dust deposition on a solar PV array.

Graphical comparison of the optimal and no cleaning strategy is given in Figure 4.9.

4.3.1.4 Scenario 4: random cleaning strategies

Three random cleaning strategies are considered and given numerically in Table 4.9 and graphically in Figure 4.7.

1. **Random cleaning 1 strategy**
   In the first strategy, random cleaning 1, a random number of PV strings are cleaned at the optimal cleaning strategy. Graphical comparison of the optimal and random cleaning strategy 1 is shown in Figure 4.10. From Figure 4.10, optimal cleaning intervals is 7 as compared to 12 for random cleaning 1 strategy. The higher cleaning intervals results in the cleaning cost for

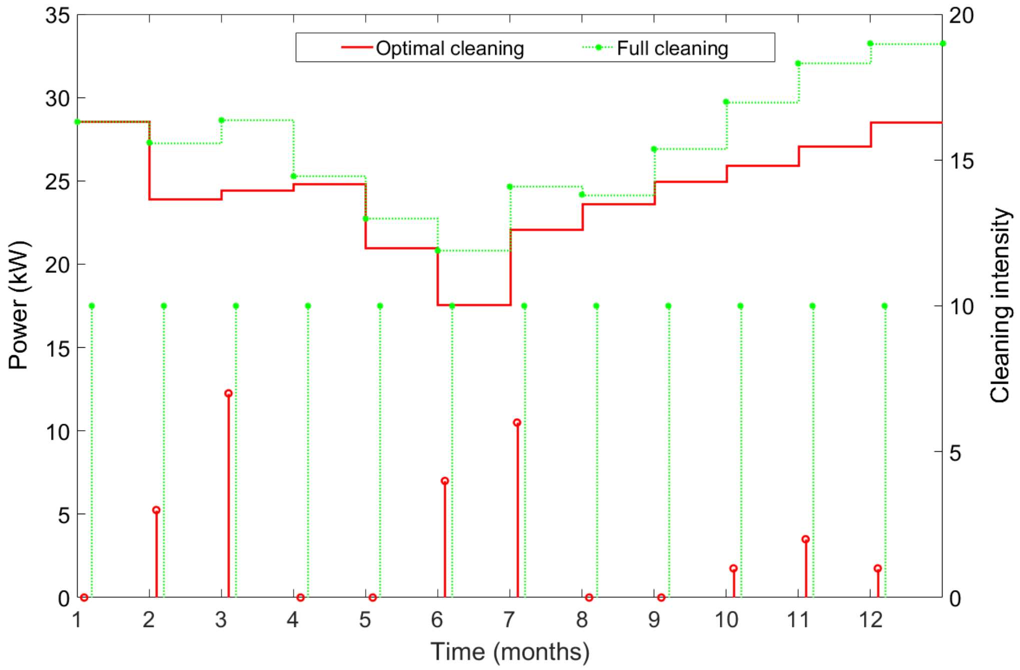


Figure 4.8. Optimal cleaning strategy vs full cleaning strategy

random cleaning 1 strategy to be R 2,340 which is more than R 1,440 for the optimal strategy. In addition, the energy generated by the random cleaning 1 strategy is higher at 35,440 kWh as compared to the 35,318 kWh generated by the optimal strategy. The net sales of the random cleaning 1 strategy are however reduced due to the higher cleaning cost.

2. **Random cleaning 2 strategy**

   For the random cleaning 2 strategy, optimal number of PV strings are cleaned at random cleaning strategies. Graphical comparison of the optimal and random cleaning 2 strategy is given in Figure 4.11. From Figure 4.11, optimal cleaning intensity is 7 which is the same as the cleaning intensity for for random cleaning 2 strategy. The cleaning costs for both cleaning strategies are therefore the same. However, the energy generated by the optimal cleaning strategy is 35,318 kWh which is more than 34,600 kWh generated for random cleaning 2 strategy. The reason for this difference lies in the time that cleaning takes place. For the optimal cleaning strategy, 10 PV strings are cleaned at the beginning of the evaluation period, 10 PV strings cleaned in the middle of the evaluation period and 4 cleaned at the end on the year as shown in Figure 4.11. For random cleaning 2 strategy, 19 PV strings are cleaned at the beginning of the year and 5 pV strings cleaned towards the end of the year. The interval between

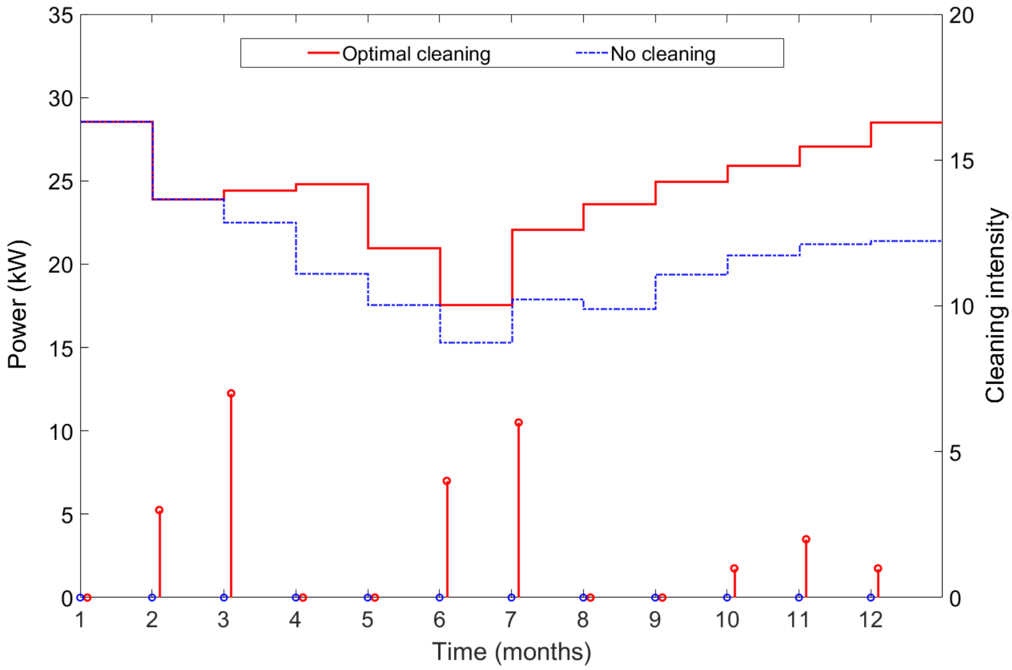


Figure 4.9. Optimal cleaning strategy vs no cleaning strategy

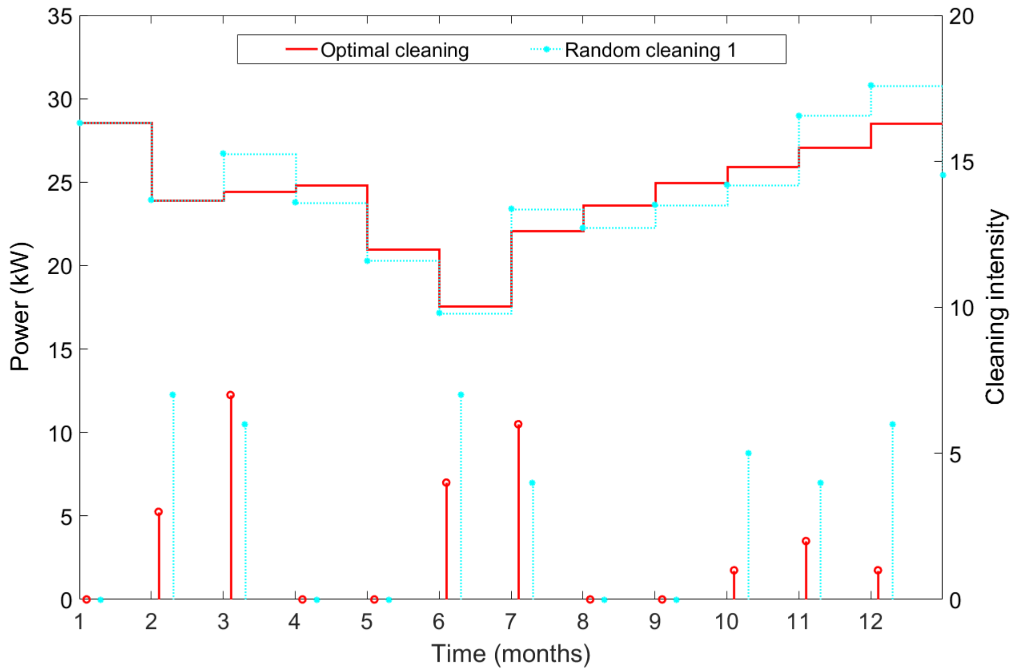


Figure 4.10. Optimal cleaning strategy vs random cleaning 1 strategy

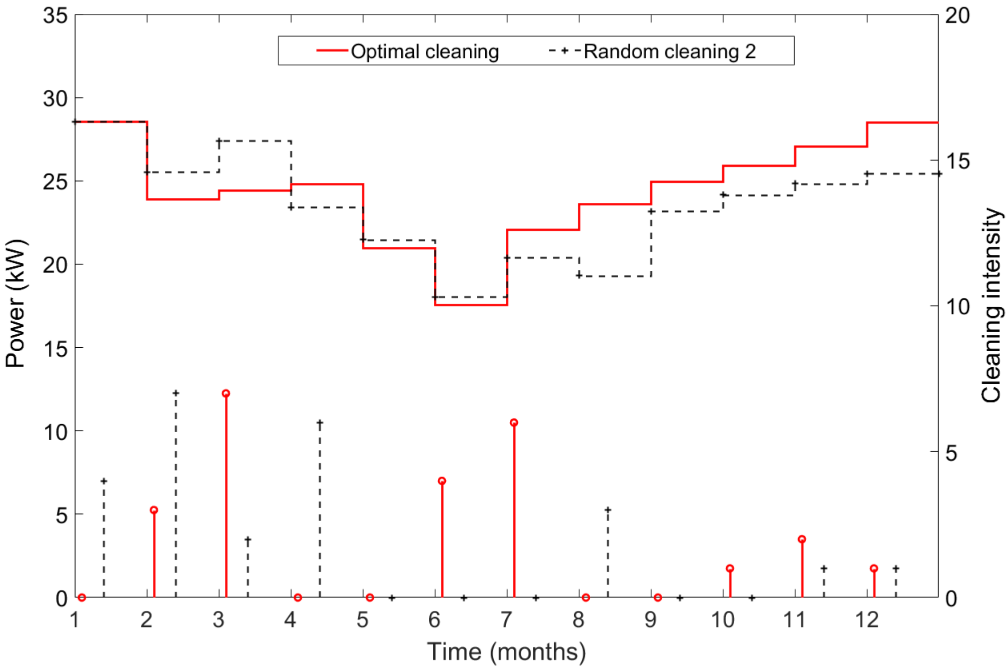


Figure 4.11. Optimal cleaning strategy vs random cleaning 2 strategy

the cleaning actions on random cleaning 2 strategy is therefore more than the interval between optimal cleaning, thereby allowing more dust to gather on the solar panels and reducing the energy generated. The net sales of the optimal cleaning strategy are therefore more.

3. **Random cleaning 3 strategy**

   Random cleaning 3 strategy involves cleaning random number of PV strings at random cleaning strategies. From Figure 4.12, optimal cleaning intervals is 7 as compared to 8 for random cleaning 3 strategy. The slightly higher cleaning intervals results in the cleaning cost for random cleaning strategy 3 to be R $2,520$ which is more than R $1,440$ for the optimal strategy. In addition, the energy generated by the random cleaning 3 strategy is higher at $36,009$ kWh as compared to the $35,318$ kWh generated by the optimal strategy. The net sales of the random cleaning 3 strategy are however reduced due to the higher cleaning cost. Graphical comparison of the optimal and random cleaning 3 strategy is given in Figure 4.12.

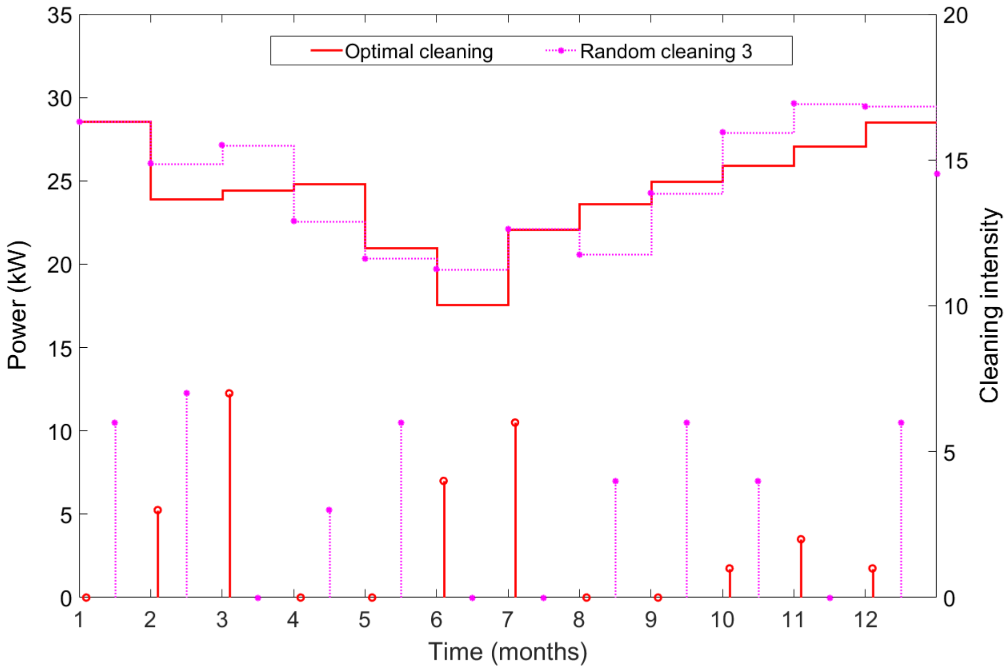


Figure 4.12. Optimal cleaning strategy vs random cleaning 3 strategy

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 CONCLUSION

Solar PV plants are prone to dust deposition. The sources of dust include the natural environment, industrial activities, weather and environmental disaster. When the dust settles on solar panels in the PV plant, it can do so in a way that all parts of the PV plant have the same amount of dust deposition. This is the ideal case. In reality, the dust may deposit more on one area of the PV plant than another, thereby creating non-uniform dust deposition. The result of such deposition is negative performance of the solar panel and PV plant. Because of the dust deposition, two challenges emerge. The first is understanding how non-uniform dust deposition occurs and its effect on a PV plant. Cleaning of PV plants has been found to be an ideal way of removing or reducing the effects of dust deposition. However, a challenge comes in when when carrying out the cleaning. For a large scale PV plant, how frequently and with what intensity should the cleaning be done while ensuring optimal use of resources and meeting set goals?

The challenges are addressed in this research by proposing an optimal cleaning schedule for PV arrays that suffer from non-uniform dust deposition. The research has been carried out with the objective of **(1)** determining how non-uniformity can be modeled mathematically, hence obtaining its patters and effects; and **(2)** determining the optimal cleaning frequency and the optimal cleaning intensity with which cleaning should be done. The proposed cleaning schedule is developed by first using the single-diode PV cell mathematical equations to obtain the output characteristics of a PV array. The effect of dust deposition on the performance characteristics of solar panels is presented using an existing mathematical model that relates dust deposition and tilt angle with transmittance. Non-uniform dust deposition is then defined and quantified mathematically. Monte Carlo simulation is applied to generate a non-uniformity dust deposition patterns. The non-uniformity patterns are developed for different scenarios. The effects of the non-uniformity of dust deposition are also determined. A cleaning optimization model is also proposed to develop a cleaning schedule that reduces the effects of non-uniform dust deposition. A case study and other cleaning schedules are used to demonstrate the superiority of the proposed cleaning schedule.

The contributions of this paper are:

1. Introduction of mathematical modeling of non-uniform dust deposition and development of non-uniformity patterns for a PV array.
2. Use of mathematical models to develop an optimal cleaning schedule for a PV array that suffers from non-uniform dust deposition. The proposed cleaning model can be used in PV plants that are installed in areas that are prone to dust deposition and experience minimal rainfall and wind.

5.2 FUTURE WORK

The future work on cleaning PV arrays affected by non-uniform dust deposition can be carried out considering the following:

1. Mathematical modeling of other other non-uniform dust deposition patterns such as:

   i Non-uniformity at PV cell level where dust deposition varies from one PV cell to another of the same solar panel.

   ii Non-uniformity on the same solar panel where the dust deposition varies from one part of the solar panel to another.
2. Include effects of cleaning by rainfall and wind, together with cleaning using collected water.
3. Consider other constraints such as availability of labor and water.

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