Optimal cleaning strategy of large-scale solar PVarrays considering non-uniform dust deposition

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Optimal cleaning strategy of large-scale solar PV arrays considering non-uniform dust deposition

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ABSTRACT

The dust deposition on top of solar panels blocks the solar insolation, causes erosion of the solar panel surface material, and also deviates the maximum power point of the solar panels' power output, which results in reductions of the panels' power outputs and accelerations on the panels' aging process. In practice, periodically cleaning efforts on the solar panels have to be conducted for dust removal, which intensifies the operational cost of many solar photovoltaic power plants. This study proposes an optimal cleaning plan for the PV plants that are prone to the dust deposition. In order to obtain the optimal cleaning plan, we first investigate the dust deposition process and develop a model to describe how PV power generation varies with the non-uniform dust deposition patterns. Then we formulate a constrained optimization model to identify the most cost-effective solar panel cleaning strategy. 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 PV strings to be cleaned at each cleaning interval. A case study is presented to show how effective the proposed optimal solar panel cleaning strategy is.

Introduction

The solar photovoltaic (PV) technology relies on solar irradiance to generate power. How much solar irradiance is received by a PV cell can be affected by fast changing factors such as cloud movement or slowly varying factor such as dust deposition. The dust deposition refers to atmospheric dust settling on top of solar PV modules. It negatively affects the solar irradiance reaching the solar PV module hence reducing their performance. Dust deposition has been found to cause efficiency reduction of the solar panels by 66% in India[1] after 6 months, and 20% reduction within 8 days of exposure in China[2]. In Saudi Arabia, the power output of solar panels reduced by 50% after 6 months exposure[3].

Factors that influence the dust deposition process on solar power systems include size of dust particles, exposure period, tilt angle, PV modules type and weather conditions. Finer scale dust particles usually cause more severe dust depositions hence more power generation losses. Laboratory studies in[4] and[5] found that PV power output decreased more rapidly with the deposition of finer dust particles such as carbon, cement, ash and volatile material. These elements call for specialized cleaning such as using sodium. Longer exposure periods cause more significant power losses because dust continues to accumulate on the PV module. The solar PV modules at smaller tilt angles gather dust more easily than those at larger tilt angles, hence performance losses are more severe at smaller tilt angles. Glass samples exposed outdoors in Egypt for 30 days resulted in transmittance losses of 21% and 11% at tilt angles of 20° and 60° respectively[6]. The level of dust deposition, as varied by these factors, can be determined by carrying out dust measurements or electrical parameters. Frequent inspections and measurements can be carried out over time, paying careful attention to precision[7]. Maintenance action can then be taken depending on the condition, a practice known as condition-based maintenance[8].

Experiments also show that dust deposition results in varied negative impacts on different solar panels technologies such as monocrystalline, polycrystalline and thin film solar cells. Monocrystalline and polycrystalline PV modules exposed for 6 months showed a better performance ratio for polycrystalline modules[3]. A spectral analysis carried out in Kuwait[9] showed that PV modules that have a wider band gap (Amorphous silicon and Cadmium telluride) were more easily affected by dust deposition than those with smaller band gaps. Weather conditions such as rainfall and wind also influence the dust deposition process. Rainfall reduces the effects of dust deposition when it falls frequently on PV modules thereby cleaning the PV module. Light rainfall in a dusty environment will however cause mud formation on the PV module leading to more losses in the transmittance. PV modules in Kuwait[10] showed an increased loss of 25% in the daily energy yield after rainfall due to the formation of mud during the rain. Wind influences dust settlement and removal on the PV modules. Weak wind promotes dust deposition as compared to a strong wind, especially in dusty or polluted areas. Dust storms also cause negative performance of solar panels with studies showing 20% loss in the power output after a dust storm[3]. Over time, the effect of dust deposition on power loss was observed to be exponential[11].

In order to maintain the power generation capacity, cleaning the dusty solar panels has become a popular preventive maintenance action in solar power plants. Existing solar panel cleaning approaches include use of electrodynamic screens (EDSs), solar panel coating, or 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 performance capacity of the solar PV module[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 PV modules[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 PV modules[13], while light rainfall in a dusty area forms sticky mud on the glass surface thereby deteriorating the power output further[10]. Strong wind sometimes works effectively to remove dust deposited on the solar PV modules, especially at high tilt angles[16], but wind can be scarce and unable to remove dust particles whose diameters are shorter than 50 μm since they tend to adhere to the PV module 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 on solar panels. 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 PV module cleaning schedules in a cost-effective manor. However, without understanding the dust deposition process, many existing studies[6,19–22] suggest a fixed-term cleaning schedule, which is not cost-effective.

In order to effectively alleviate the negative impact from the dust deposition on the solar panel surfaces, many research activities have been conducted to study the dust deposition dynamics with considerations of solar panels' materials, tilt angles, and geographical locations. Main purpose of these investigations is to build mathematical models that describe how transmission loss varies with dust deposition density with respect to tilt angle, dust particle properties, and environmental factors such as dust event, humidity, and tracking mechanisms of solar panels. These dust deposition models are further applied to predict the power generation loss of 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 is developed in[23] by based on the Lambert-Beer-Bouguer law and Monte Carlo simulation. The model focuses on the effects of dust increase, which concludes that the transmittance of the sunlight suffered exponential decay with increasing dust density. Several regression models have been developed to characterize the relationship between the transmission reduction and dust density, with the support of physical experiments. Experiments in[24] reveal that dust particles with a diameter of 80 μm and an area density of 250 g/m^2 will reduce PV power generation by 84%. In[1], a regression model shows strong correlations between the transmission reduction and dust density based on the experimental observations. In[6], an empirical correlation that enables predicts the decay in transmittance of tilted glass samples is derived. The study[20] proposed a polynomial regression model, which correlates dust deposition density with transmittance. Vast application of computational fluid dynamics (CFD) method in investigating dust deposition variation in wind air flow, makes it also applicable for the investigations on how dust deposition is characterized for solar PV system installed at the ground level. For instance, the studies[25] and[26] have applied the CFD to investigate the mechanisms and behaviors of dust deposition on ground-mounted solar PV systems.[26] focused more on how the size of particles and tilt angles affect dust deposition. To cater for multiple PV cleaning criteria, a multi-criteria decision making model[27] was used to rank and select the optimal PV cleaning method.

These existing dust deposition modeling efforts have properly characterised the transmittance losses of dirty solar panels. Practically, the dust deposition usually distributed unevenly across the surface of a single PV module or in a large-scale PV array. The nonuniform dust deposition on the solar panels results in more significant power generation losses due to dust-induced shading effects on the PV modules[9,28]. The in-field observations in[29] show that the dusty areas will result in a higher temperature which consequently reduces the power generation efficiency. In addition, the non-uniform dust pattern also causes the solar panels' maximum power point tracking (MPPT) to shift. When dirty PV modules are connected together with cleaned (or less dusty) ones in the same 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 PV modules clean. The cost of labor and water, especially in areas with water scarcity, and loss of energy yield are the key factors to develop cleaning schedules with minimum cleaning cost while maintaining solar power generation. Many existing studies have made significant efforts to determine the cleaning schedules for the soiled solar PV plants. Since there is a trade off between the cleaning cost and additional solar power generation, the cleaning schedules for solar panels with dust depositions can be optimised. In the literature, a number of studies suggest a fixed cleaning schedules with optimisation. For instance,[30] determines a fixed clean interval according to the predefined power loss and dust concentration levels on the solar panels. In[31], 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[32] comments that beneficial cleaning is achieved if the solar panel soiling rate is more than 7%, while the fixed weekly cleaning policy is too costly. Ref[33] suggests a financial approach in determining the cleaning interval using a model employing regression and Artificial Neural Network to determine performance of the PV system depending on dust deposition and surrounding temperature of the PV modules. Some other studies used optimisations to find the best variable cleaning schedules over a certain evaluation period. In[34], the 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. Ref[35] applies a condition-based cleaning strategy to clean concentrating solar power systems, considering the rain probability and reflectivity degradation of the solar collectors. The advantage of variable cleaning schedules is brought out in[36] and[37] who found that maximum revenue and PV energy yield can be determined when a variable optimum cleaning strategy was determined and when it with different seasons in a year.

From the literature review on the dust deposition modelling and cleaning scheduling optimisation for soiling solar panels, we observe that more research investigations are necessary to further improve the cleaning schedules of the soiling solar panels. Comparing to the existing studies, our study is novel and special in the following aspects: 1) based on existing models of the dust deposition process, we model the solar power output of a PV array while considering the effects of non-uniform dust depositions on them. This is novel since majority of the existing studies focus on modelling the dust deposition process on a single solar panel; and 2) considering the dust deposition dynamics, cleaning cost, and extra power generation due to cleaning, we intuitively believe that there exist an optimal solar panel cleaning strategy with a variable cleaning schedule. Since we formulated the relationship between the non-uniform dust deposition on a solar PV array and its power output, it also offers an extra flexibility that only the most dusty solar panels are cleaned first instead of cleaning the entire PV plant at each cleaning interval, in order to effectively reduce the cleaning cost whilst maintaining the plants' power generation capacity. We thus formulate an optimal cleaning problem based on the models of dust deposition process, the single diode PV cell model[38], and the variation of solar array power generation and non-uniform dust deposition patterns. The objective function is the net benefit associated with the cleaning of soiling solar panel in a solar plant. The decision variables are the number of dirty 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 binary linear constrained optimisation problem is properly solved using integer linear programming[39] in MATLAB. Optimal solutions to a case study in a solar plant consist of 100 poly-crystalline PV modules show that a maximum net benefit is achieved by applying the optimal cleaning strategy comparing to the full cleaning and no cleaning solutions.

Problem formulation

In this section, a constrained optimisation problem is formulated to solve the optimal PV array cleaning problem based on the modelling of PV array power output with nonuniform dust deposition patterns.

Solar PV array modeling

The single diode PV cell model is widely applied in modeling the current, voltage, and power output from a single PV cell[40]. The circuit that shows the electrical characteristics of a PV cell is given in Figure 1. and the current from the cell is

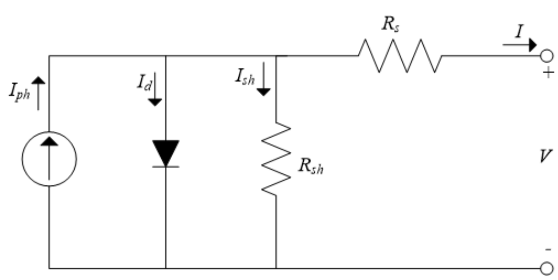


Figure 1. Electrical representation of a Single Diode PV cell[40]

$$I = I_{ph} - I_d - I_{sh}, \tag{1}$$

where I_{ph}, I_d and I_{sh} are the photogenerated current, current from the diode , and the current through the shunt resistance in Amps, respectively. The I_{ph} is dependent on irradiance G and temperature of the cell T_c in $^{\circ}C$ and,[41]

$$I_{ph} = \frac{G}{G_{ref}}(I_{ph,n} + k_i(T_c - T_{c,r})), \tag{2}$$

where G and G_{ref} are the real-time and reference solar irradiance in W/m^2, respectively. $I_{ph,n}$ is the light-generated current in Amps at industry approved conditions. T_c and $T_{c,r}$ are the real-time and reference cell temperatures in Kelvin (K), respectively, and k_i is current temperature coefficient in A/K. The cell temperature T_c is given by:

$$T_c = T_a + \left(T_N - T_{c,ref}\right)\frac{G}{800}, \tag{3}$$

such that T_a and T_N are the surrounding air temperature and nominal operating cell temperature respectively. Diode current is described by,[42]

$$I_d = I_o\left[\exp\left(q\left(\frac{V+IR_s}{AkT_c}\right)\right) - 1\right], \tag{4}$$

where q is the magnitude of electronic charge which is 1.602×10^{-19} C, V is the DC output voltage in volt. R_s represents series resistance in Ohm, A represents the diode ideality factor and k represents the Boltzmann constant[43]. I_o, the saturation current, has a strong dependence on temperature[42]

$$I_o = I_{o,ref}\left(\frac{T_c}{T_{c,ref}}\right)^3 \exp\left(\frac{qE_g}{Ak}\left(\frac{1}{T_{c,ref}} - \frac{1}{T_c}\right)\right), \tag{5}$$

where $I_{o,ref}$ is the reference saturation current, T_c and $T_{c,ref}$ are the present and reference cell temperature, E_g is the band gap energy[43]. The shunt current is given by:

$$I_{sh} = \frac{V+IR_s}{R_{sh}}, \tag{6}$$

where R_{sh} is the shunt resistance. Substituting Equations (4) and (6) into Equation (1), the PV cell output current in[42] is denoted by

$$I = I_{ph} - I_o\left(\exp\left(\frac{V+I.R_s}{A.V_T}\right) - 1\right) - \frac{V+I.R_s}{R_{sh}}, \tag{7}$$

where

$$V_T = \frac{kT_c}{q}. \tag{8}$$

Dust deposition on solar panels

As discussed in the introduction section, existing dust deposition models are developed by analytical approach, regression analysis, and computer aided simulation. In this study, the model developed in[6] was found most suitable due to its simplicity, robustness, and less computational burden. The model in[6] is a data driven model, which is developed based on data collected over a long time period without cleaning, across various weather conditions in a subtropical region. In[6], field measurements are also performed on the dust deposition density ρ_{D0} at various tilt angles β. In[6], ρ_{D0} is measured at the horizontal when $\beta = 0°$. ρ_D at any β can be estimated using Equation (9)[44]:

$$\rho_D(\beta) = -8.5 \times 10^{-3}\rho_{D0}\beta + 0.82\rho_{D0}. \tag{9}$$

Dust deposition reduces the irradiance to the PV cells, a process known as transmittance reduction. The relationship between transmittance reduction and dust deposition is described by Equation (10)[6]:

$$\left(1 - \frac{\tau}{\tau_{clean}}\right)\% = y_1 \,\mathrm{erf}\left(y_2 {\rho_D}^{y_3}\right) \tag{10}$$

where τ and τ_{clean} are the solar transmittance of the dusty and clean PV modules, respectively, $\mathrm{erf}(\cdot)$ is the Gauss error function which incorporates dust deposition as the explanatory variable[45] and $\left(1 - \frac{\tau}{\tau_{clean}}\right)\%$ is the percentage reduction in glass transmittance. y_1, y_2 and y_3 are constants given by 34.37, 0.17 and 0.8473, respectively[6].

Since the dust deposition on solar panels causes power generation loss by preventing the solar irradiance from reaching the PV cells, the solar radiation that is finally absorbed (G) by a dusty solar panel is calculated from the solar radiation (G_r) and the transmittance rate of the solar panel (τ)[44]:

$$G = G_r\tau \tag{11}$$

Non-uniformity of dust deposition on solar panels

For any given solar array, the dust deposition on the panels is uniform when following conditions are satisfied: 1) the solar panels are identical in terms of technical specifications, age, and tilt and azimuth 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 depositions on the solar panels are uniform. Instead, the dust depositions are non-uniform, even for a single solar panel. In most of the solar power plants, the solar panels are the minimum assembling unit for power generation, whose output power are measurable under various working conditions.

The reduction in solar irradiance from Equation (11) can be expressed as a percentage which varies from 0% to 100%, where 0% indicates no dust deposition and 100% indicates that dust deposition completely blocks out the irradiance. The percentage reduction in irradiance for a hypothetical PV array is shown in Figure 2. For any PV string in Figure 2, its current output will be limited by the current generated by the most dusty solar panels in that string. This limitation leads to loss of power output. For a PV string having n solar panels, the PV string current and voltage are given by Equations (12) and (13)[46]:

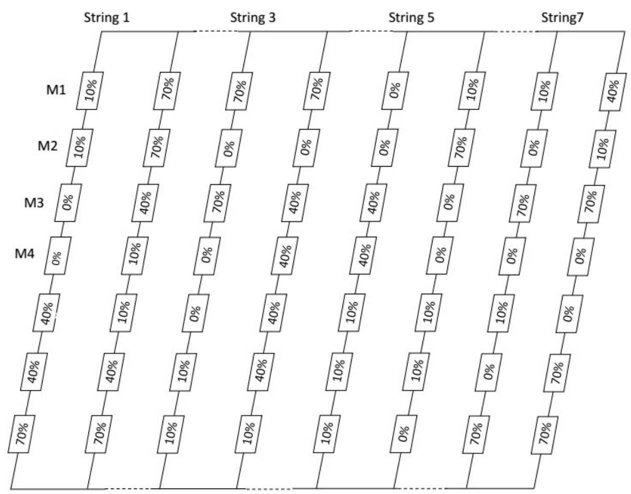


Figure 2. Non-uniform dust deposition for a PV array

$$I_s = min(I_{m1}, I_{m2}, I_{m3}, ..., I_{mn}), \tag{12}$$

where I_s is the current through the PV string, and $I_{m1}, I_{m2}, I_{m3}, ..., I_{mn}$ are current outputs from each solar panel. The voltage across each PV string is given by:

$$V_s = \sum_{i=1}^{n} V_{mn}, \tag{13}$$

where V_s is the voltage across the PV string, V_{mn} is the voltage across each solar panel in the PV string, from solar panel i, $i \in [1, n]$. The power from a PV string therefore is given by:

$$P_s = V_s \times I_s. \tag{14}$$

An illustrative example is presented to show the negative impact of the non-uniform dust deposition on solar panels. Figure 2 shows a PV array with 8 PV strings, each having 7 solar panels. Each dusty solar panel has a hypothetical value of τ. Rows M1-M4 and PV strings 1-3 in Figure 2 form a 4×3 PV array. Suppose each solar panel has a maximum rating of 350.39 W_p, 6.302 A and 55.6 V. Using Equation (1) to (14), the current and voltage corresponding to the maximum power points together with the maximum power output values are calculated and given in Table 1.

From Table 1, it is observed that the higher τ due is to dust deposition, the lower the current is generated; $M1$ in PV string 2 has the highest shading percentage of 70% and gives a current output of 2.516 A. The resultant current in the PV string is therefore also 2.516 A, even though PV module $M4$ in the same PV string has a τ of 10% and higher current of 5.677A. The non-uniform dust deposition patterns thus cause the PV array power output to reduce from the maximum $4,204.73$ W to $2,354.37$ W.

Bypass diodes are connected in the solar panels to prevent hot spots during partial shading caused by the dust deposition, which however generates multiple maxima on the I-V and P-V curves. When multiple maxima are formed on the P-V curve,

Table 1. Non-uniformity on PV modules with equal wattages

		τ (%)	Current at MPP (A)	Voltage at MPP (V)	Max power (W)
String 1	M 1	10%	5.677	55.3	313.92
	M 2	10%	5.677	55.3	313.92
	M 3	0%	6.302	55.6	350.39
	M 4	0%	6.302	55.6	350.39
String 2	M 1	70%	2.516	55.3	134.6
	M 2	70%	2.516	55.3	134.6
	M 3	40%	4.407	54.8	241.5
	M 4	10%	5.677	55.6	350.39
String 3	M 1	70%	2.516	55.3	134.6
	M 2	0%	6.302	55.6	350.39
	M 3	70%	2.516	55.3	134.6
	M 4	0%	6.302	55.6	350.39
Array					**2354.37**

there are potential risks that the maximum power point tracking (MPPT) sometimes tracks a local MPP as opposed to the global MPP.

Solar panel cleaning optimization

In this study, we aim to identify the optimal cleaning strategy for large scale solar power plants that are prone to dust deposition. To prioritise the cost-effectiveness of the cleaning strategy, we 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 the solar panel cleaning. The net benefit is indeed 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 maintenance interval. The solar PV cleaning machine uses brushes, water and soap. Power output of a solar panel is restored to the original capacity after cleaning.

The objective of this study therefore is to maximize the additional revenue generated due to cleaning and is expressed as:

$$J = \sum_{k=1}^{K} \sum_{s=1}^{S} \left(R_s(k) - \overline{R}_s(k) \right), \tag{15}$$

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, s is the index of PV strings $s = 1, 2 \ldots, S$, K is the total number of time intervals and k is the index of time interval $k = 1, 2 \ldots, K$. The net revenue generated from a clean PV string at any time k is the difference between the sales and the cleaning cost at time k, such that:

$$R_s(k) = P_s(u_s(k))h(k)f(k) - C_s u_s(k), \tag{16}$$

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,

$$u_s(k) \in \{0, 1\} \text{ for } 1 \leq k \leq K, \tag{17}$$

where $u_s(k) = 0$ indicates not to clean and $u_s(k) = 1$ indicates the 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 cleaning cost 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

$$\overline{R}_s(k) = \overline{P}_s(x_s(k))h(k)f(k), \tag{18}$$

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 (15) is subject to the following constraints. 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:

$$0 \leq \sum_{s=1}^{S} u_s(k) \leq S. \tag{19}$$

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

$$P_s^{min}(k) \leq P_s(k) \leq P_s^{max}(k), \tag{20}$$

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

Optimization algorithm

The optimisation problem in Eqs. (15) - (20) is an integer linear programming problem, which can be solved by the Optimization Toolbox in Matlab[39]. The objective function is formulated in the form:

$$maximize_u \quad f(u), \tag{21}$$
$$subject\,to \quad lb \le u \le ub, \tag{22}$$
$$Au \le b \tag{23}$$
$$u \in \{0,1\}. \tag{24}$$

Case study

In this section, a case study presented to illustrate how advantageous the proposed solar panel cleaning optimisation model is.

Background

In South Africa, a solar PV plant consists of 100 polycrystalline solar panels. Technical parameters of the solar panels given in Table 2 are used as initial values for simulation and obtained from[47] except for E_g, K and q which were obtained from[43]. The solar irradiance and dust deposition records for location of the solar PV plant between 2012 and 2013 are given in Table 3[48]. Irradiance data was obtained from the Southern African Universities Radiometric Network. The 100 solar panels form a 10 by 10 PV array. I-V and P-V curves for their clean and Non-uniform dusty array conditions are plotted as in Figure 4. In Figure 4a, a maximum power of 34.50 kW can be seen. At this maximum power point, the current and voltage are 60.20 A and 572.98 V, respectively. As time goes by, dust deposition occurs. Figure 3 shows he non-uniform dust deposition pattern in June.

Table 2. 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_N	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}

Table 3. 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 P-V plot in Figure 4b has more than one peak due to the shading effects by dust. The highest power peak (GMPP) is 19.12 kW, corresponding current and voltage are 35.83 A and 533.20 V, respectively. A comparison of the simulation results of the clean and dusty PV array is given in Table 4. In Table 4, the maximum power reduces by 44.56%, whilst the current and voltage at the MPP are reduced by 40.48% and 6.94%, respectively when the solar panels are getting dusty.

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 in every months in an effort to maintain the goal. Regular cleaning cost of the solar panels

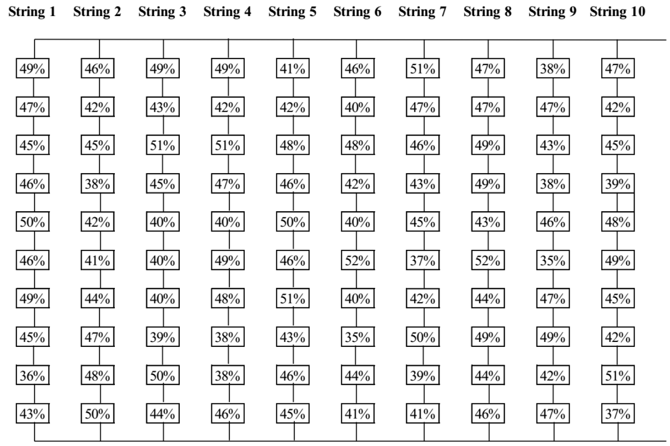
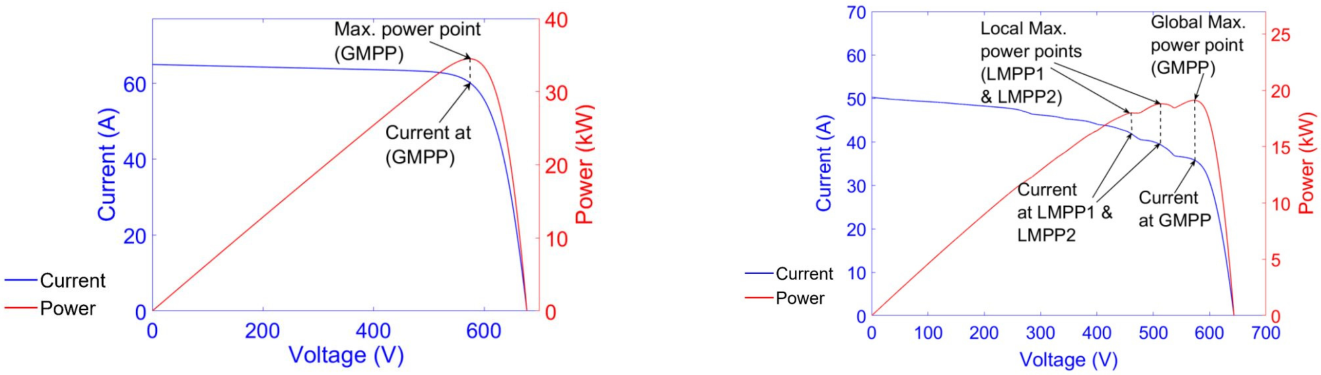


Figure 3. Non-uniform dust deposition pattern in June



(a) Clean solar panels

(b) Non-uniformly dusty solar panels

Figure 4. Current-Voltage and Power-Voltage curves

includes labour cost and water consumption. The labour cost is R 20 per hour (1 U.S. dollar ($) = 18.09 South African Rand (R)). 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[49].

Optimization results and discussions

As introduced in Section , the solar plant cleans all the solar panels once every month and all solar panels are cleaned each time. The cleaning efforts are effective however may not be cost-effective. The plant owners are keen on a prioritised cleaning strategy. Based on the modeling and understanding of the solar panels dust deposition characteristics, and the relationships between power generation and the dust deposition, a constrained optimisation problem is formulated in Section . 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 5, where the dual-simplex algorithm is selected as the optimization algorithm; maximum nodes and the maximum time are given in addition to the tolerances of the function value and constraint. A starting point u_0 and the boundaries of the design variables are also given.

To highlight the advantage of the presented optimal solar panel cleaning model, we also analysed performances of other solar panel cleaning approaches, namely:

Full cleaning: refers to the case when all the PV strings are cleaned at every time interval.

No cleaning: no solar panel is cleaned over the entire evaluation period.

Table 4. Comparison of clean and non-uniformly dusty solar panels.

	Clean solar panels	Dusty solar panels	Change (%)
Max. current (A)	60.20	35.83	−40.48%
Max. voltage (V)	572.98	533.20	−6.94%
Max. power (kW)	34.49	19.12	−44.56%

Table 5. Optimization settings.

Category	Options
Algorithm	dual-simplex
TolCon	10^{-6}
TolX	10^{-5}
Max nodes	10000000
Max time	7200 s

Random cleaning: refers to 1) clean random number of PV strings at optimal cleaning schedules; 2) clean optimised number of PV strings at random cleaning schedules; and 3) clean random numbers of PV strings at the random cleaning schedules.

Optimal cleaning

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 5 and numerically in Table 8. 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 5. In Figure 5, the power output at the start of the evaluation period is 28.57 kW. Continued dust deposition with time reduces the PV power generation. 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.

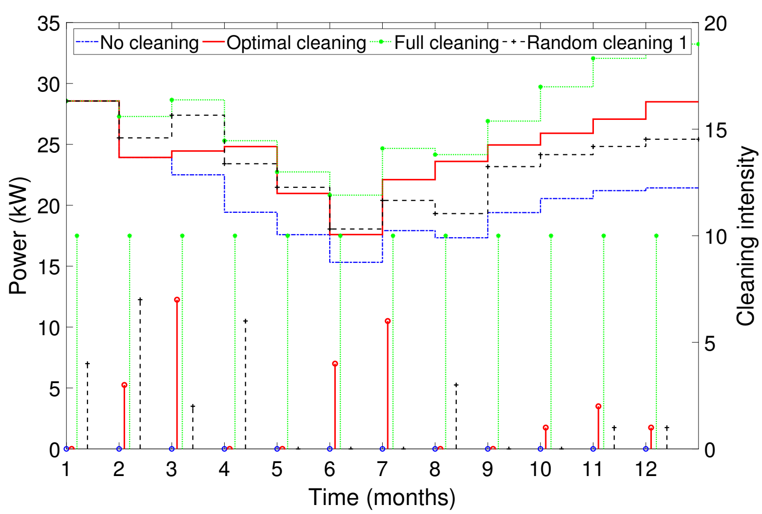


Figure 5. Optimal cleaning strategy

Had there been no cleaning, the power would have reduced to 22.50 kW as shown by the the ‘no cleaning’ curve in Figure 5. Another factor that contributes to the change in power level is the solar irradiance. As can be observed from Figure 5, solar power generation varies even with full cleaning strategy implemented. This is mainly caused by the changes of the local 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 are the solar panels with high level of dust deposition that generate the least amount of power output. Changes in the PV string power generation are shown in Table 6. 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

Table 6. Solar power generation (kW) with optimal cleaning.

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

Figure 5, increasing the array power output to 22.10 kW. The total power and energy generated throughout the evaluation period are 292.48kW and $35,318$ kWh. The associated cleaning cost is R $1,440$ which gives net sales of R $26,461$.

Table 7. 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

Table 8. 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

Full cleaning

Without considering optimisation, some solar power plant may decide to clean all the 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 5. A full cleaning strategy does ensure the maximum solar power generation, which is however not the most beneficial approach due to the extra cleaning cost. Detailed cost analysis for the full cleaning strategy is shown in Table 7.

No cleaning

When the dusty solar panels are not cleaned, the power generation of the solar PV array reduces continuously and significantly as shown in Figure 5. The analysis for the 'no cleaning' strategy clearly illustrates how dust deposition negatively affects solar panels. The net sales are R 23,706, which is the worst of all cleaning strategies considered, as shown in Table 7. The power and financial analysis for the no cleaning strategy clearly shows the negative consequence of dust deposition on solar panels.

Random cleaning

The optimal solar panel cleaning strategy returns the detailed PV strings to be cleaned at a specific time instant. For comparison purpose, financial analyses of the three random cleaning strategies are calculated and shown in Table 8. The first random cleaning strategy is also shown in Figure 5. For the first random cleaning strategy, random number of PV strings are cleaned at optimal cleaning schedules. For the second random cleaning strategy, optimised number of PV strings are cleaned at random cleaning schedules and for the third cleaning strategy, random numbers of PV strings are cleaned at random cleaning schedules.

Uncertainty analysis

According to[50], uncertainties can be classified into quantifiable and non-quantifiable uncertainties. The non-quantifiable uncertainties mainly refer to human errors involved in the experimental process, i.e., meter reading errors. In this uncertainty analysis, we only focus on the quantifiable uncertainties. The quantifiable uncertainties mainly include three components such as the measurement uncertainty, sampling uncertainty and modelling uncertainty. In this study, sampling uncertainty does not apply since each individual solar panel is covered in the formulation. The measurement uncertainty is negligible as sophisticated measurement instruments are used to measured the mass of dust deposition. The critical uncertainty is therefore the modelling uncertainty, which influences the optimisation outcome. Detailed analysis on the modelling uncertainty against our optimisation results are provided as follows. The uncertainty level can be quantified in terms of the combination of precision and confidence interval, as shown by Equation (25):

$$\hat{Y} = \bar{Y} \pm t \times S_E, \tag{25}$$

where $\hat{Y}$ and $\bar{Y}$ refer to the model predicted outputs and the mean of the outputs, respectively; t is the t-value for a t-distribution, which is linked to a certain confidence interval. For instance, the t-value for a 95% confidence interval is 2.23; and S_E is the root mean square error of the model. The relative precision is calculated by

$$\frac{t \times S_E}{\bar{Y}}.$$

In our study, Equation (9) is applied to predict the dust deposition level[6]. The S_E value of the model is 0.015 g/m^2. Based on dust values from Table 3, the estimate dust deposition $\rho_D(\beta)$ can be determined, and the associated relative precision at 90% confidence interval is 2.24%. According to the dust deposition uncertainties, we calculated the corresponding optimisation outputs again, which are presented in Figure 6. A tabular comparison for the uncertainty analysis is shown in Table 9. The

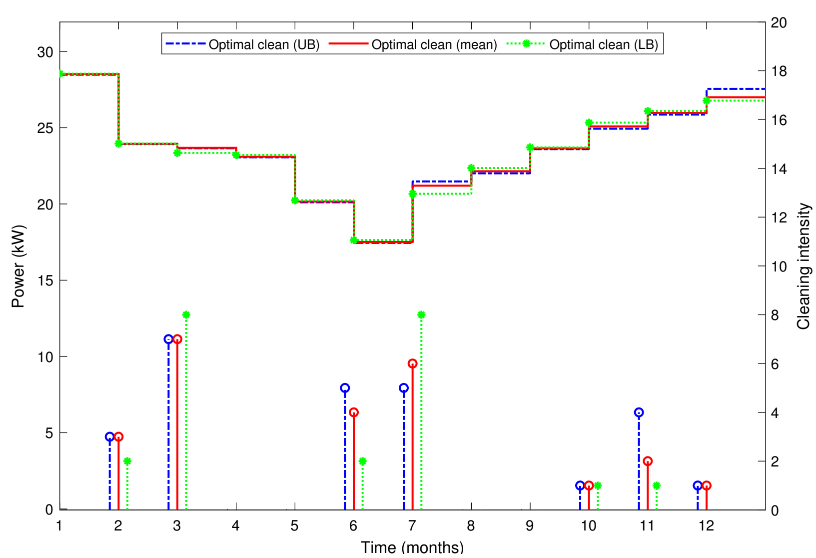


Figure 6. Optimal cleaning when considering the modeling uncertainty

number of PV strings cleaned and the associated costs increase and decrease with respective variation in dust deposition levels. The cleaning interval however remained the same for increased dust deposition levels. In Table 10, the PV strings to be cleaned are specified.

Table 9. Uncertainty analysis

	Lower bound	Optimal cleaning	Upper bound
No. of cleaned PV strings	22	24	26
No. of cleaning intervals	6	7	7
Cleaning cost (R)	1,320	1,440	1,560
Electricity generated (kWh)	35,326	35,318	35,325
Electricity sales (R)	27,907	27,901	27,907
Net sales (R)	26,587	26,461	26,347

Table 10. PV strings to be cleaned when considering the modelling uncertainty.

Month	Lower bound	Optimal cleaning	Upper bound
January	-	-	-
February	6,7	3,6,7	3,6,7
March	1,2,4,5,8,9,10	1,2,4,5,8,9,10	1,2,4,5,8,9,10
April	-	-	-
May	-	-	-
June	6,7	3,6,7,9	3,6,7,8,9
July	1,2,4,5,8,9,10	1,2,4,5,8,10	1,2,4,5,10
August	-	-	-
September	-	-	-
October	6	6	6
November	7	7,9	3,7,8,9
December	-	3	5

Conclusion

Dust deposition on solar panels, especially when non-uniform, lowers the output from solar plants. Understanding the how non-uniform dust deposition can be modelled mathematically and its effects is important. Since cleaning is necessary to restore solar PV plant output, a constrained optimization model to carry out optimal cleaning in dusty areas is proposed in this study. Through simulation, the models aims to identify the cost effective cleaning plan for solar panels while maintaining profits and power output. The optimal cleaning schedule obtained is compared to other cleaning schedules including full, random and no cleaning to demonstrate its cost effectiveness. Lastly, robustness of the optimal cleaning plan against fluctuations dust deposition is demonstrated through modelling uncertainty. Since PV installations are increasing, further work from this study can consider modelling non-uniform dust deposition levels that vary from cell to cell and include effects of weather changes.

Availability of data and materials

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions statement

D. Simiyu, writing the original draft; X. Ye, conceptualization, methodology, and supervision; X Xia, supervision; and Y. Hu, conceptualization, and funding support. All authors reviewed and edited the manuscript.

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