Scientific African 8 (2020) e00459

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

A novel approach to Solar PV cleaning frequency optimization for soiling mitigation

Kudzanayi Chiteka[a,*], Rajesh Arora[a], S.N. Sridhara[a], C.C. Enweremadu[b]

[a] Department of Mechanical Engineering, Amity University Haryana, Gurgaon-122413, India
[b] Department of Mechanical and Industrial Engineering, University of South Africa, Florida, South Africa

ARTICLE INFO

Article history:
Received 1 May 2020
Revised 19 May 2020
Accepted 22 June 2020

Keywords:
Solar photovoltaic
Soiling
Modelling
Metaheuristic
Solar PV cleaning

ABSTRACT

Soiling is a major issue that can be a drawback to the wider deployment of solar photovoltaic systems. In this study, the influence of soiling on energy loss in Muzarabani, Zimbabwe was investigated. The daily and monthly variations in energy generated and soiling were also studied. An empirical soiling loss model was developed based on the experimental studies. It was revealed that soiling is not uniform with each passing day but rather depends on the daily differences in weather conditions. Soiling was observed to be high during the period from July to November and was less in May and June. Particle Swarm Optimisation was employed to minimise the number of days between cleaning events. Cleaning was found to be necessary every 15 days to minimise the losses due to both frequent cleaning as well as losses caused by not cleaning the panels.

Nomenclature and Abbreviations

C_c (US$)	cost of cleaning
CFD	Computational Fluid Dynamics
C_T (US$)	total cost
E_a (kWh)	actual power generated
E_e (kWh)	expected power generated
I_{mp} (A)	current at maximum power
I_{sc} (A)	short circuit current
L_s (%)	soiling loss
N	number of days between cleaning intervals
NOCT	Norminal Operating Cell Temperature
P_a (W)	power generated by the solar PV array
PSO	Particle Swarm Optimisation
PV	photovoltaic
R_s (%)	soiling ratio
S_h (hours)	peak sunshine hours

* Corresponding author.
E-mail address: tavakudzira@gmail.com (K. Chiteka).

https://doi.org/10.1016/j.sciaf.2020.e00459

STC	Standard Test Conditions
T (US$)	energy tariff
T_a (°C)	ambient temperature
T_{ref} (°C)	reference temperature
V_{mp} (V)	voltage at maximum power
V_{oc} (V)	open circuit voltage
W_p (W)	peak power
η (%)	efficiency

Introduction

The use of fossil fuels has accelerated environmental degradation and is causing global warming. It is necessary to avoid fossil-based fuels and adopt newer and cleaner alternative sources of energy. Solar energy is such an alternative source of energy which can supply the global energy needs without much negative impacts to the environment. The global capacity of solar photovoltaics (PV) is growing and the total installed capacity is expected to increase to the order of Terawatts in the coming years [1,2].

The use of solar energy, however, has its own challenges particularly soiling which is the build-up of foreign particles on the solar photovoltaic collector surface. Soiling is one of the major issues that can act as a drawback in the wider adoption of solar PV technology since up to 70% of the power may be lost due to soiling [3,4]. Soiling reduces the transmissivity of light onto the solar cell and hence the solar cell efficiency is negatively impacted [5,6]. Soiling being both a natural and anthropogenic phenomena is largely dependent on the location as such different locations have varying soiling characteristics [7]. It is unfortunate that those areas with high insolation are also prone to high dust levels [8].

Studies have been carried out to understand the impact of soiling on solar PV performance and the influence of several soiling variables have been widely investigated. For example, Lu et al. [9] investigated the photovoltaic soiling on the windward side of an isolated building using Computational Fluid Dynamics (CFD). The influence of particle sizes, dust particle quantities and gravitational force on rate of deposition was evaluated in their study. The results revealed a maximum deposition rate of 0.28 % for 10 μm dust particles while the 50 μm particles had the minimum deposition rate of 0.13 %. The study also showed that the gravitational effect was significant for particles sizes greater than 5 μm. An investigation by Pulipaka and Kumar [10] revealed that both the tilt angle and particle size composition influence the amount of soiling experienced on a PV surface. The study also revealed that soil samples with larger dust particles cause more soiling. Griffith et al. [11] investigated the influence of soiling on mirror surfaces of a Concentrated Solar Power (CSP) plant in South Africa. Their study revealed a daily loss in spectral reflectivity of 0.5 %.

Many cleaning approaches have been proposed in literature to mitigate the negative impacts of soiling. Such cleaning techniques can be classified as mechanical, material based or natural where mechanical based involves the physical cleaning using either humans or some form of equipment such as robots [12,13]. The materials approach focuses on materials such as super hydrophobic or hydrophilic materials which prevents dust accumulation on the solar panel [14–16]. Natural mitigation processes include wind and rain which can be used for the cleaning process.

Patil and Mallaradhya [17] proposed a wiper cleaning system for dust removal on solar PV collectors and approximately 1.6 % to 2.2 % improvement in power generated was realised due to sustained use of the wiper cleaning mechanism. A study by Al-Housani et al. [18] revealed that microfibre and vacuum cleaner systems are among the best cleaning mechanisms and are capable of improving power generation by 6 %. However, vacuum cleaner systems were found to be more costly when compared to microfibre-based mechanisms. In another study by Akbar and Ahmad [3], an automatic water free vacuum blower cleaning system was developed and 18 % – 20 % improvement in energy was realised. A study at King Abdulaziz University (KAU), Jeddah, Saudi Arabia by Alghamdi et al. [6] recorded a power increase above 27 % for a water based cleaning system while module vibration and air jets were not as effective in soiling removal.

Although different cleaning mechanisms and methods have been proposed, literature reveals the need to optimise the cleaning frequency to minimise financial losses and maximise energy generation. A study was carried out to optimise the installation configuration to cater for the influence of both irradiance and soiling in Portugal and the cleaning schedule was further optimised [19]. The optimisation was found to increase the annual energy production and periodic cleaning was recommended between the month of April and September. Another investigation proposed the approximation of the cleaning frequency in a desert environment [20]. The results suggested a 5 % power reduction and accumulation density of 2 g/m^2 as the criteria for cleaning. Further, it was established that the optimum cleaning interval in the desert environment studied is 20 days.

Optimisation of the cleaning procedure is a necessity and this involves finding a balance between the cost of cleaning and the cost of not cleaning [21]. While periodic cleaning is justified, too frequent cleaning intervals result in huge financial losses while too long periods between cleaning intervals result in huge energy losses [22]. Naeem and Mani [13] studied the optimal cleaning frequency for soiled PV modules in Arizona, USA. The results showed that cleaning was not necessary for panels with 20° tilt angle or higher. A generic study for the Middle East by Abu-Naser [21] employed quantitative analysis in optimising the cleaning frequency of a hypothetical 1MW solar power plant. The results showed that the optimal number of days between successive cleaning intervals is 22 days. It was further concluded that the study can be employed anywhere within the Middle East region. Karkee and Khadka [22] further developed the same model by Abu-Naser [21] and introduced

Table 1
Solar panel specifications.

JA Solar panel specifications		
1	W_p (W)	400
2	I_{sc} (A)	10.18
3	V_{oc} (V)	50.4
4	V_{mp} (V)	41.1
5	I_{mp} (A)	9.74
6	η (%)	19.7

Fig. 1. Installation at Muzarabani rural district council.

absolute hourly loss in conversion efficiency and optimised the cleaning frequency to minimise financial losses and also to reduce the payback period. In a study in Pakistan, Ullah et al. [23] worked on optimising the cleaning schedule for PV modules in Lahore, Pakistan. The influence of tilt angle and the method of cleaning, i.e. whether manual or automatic was considered in the optimisation procedure. The results of optimisation revealed the need to clean once every three weeks when using the manual cleaning method. In South Africa, an attempt to optimise the cleaning schedule of a solar PV power plant was done by Solend [24] in Kalkbult, South Africa. An analytical approach was used where cleaning was found to be necessary when the cost of energy lost is more than the cost of cleaning. The results revealed that cleaning was not required since it would take 47 days to clean the whole PV plant. Further it was noted that the cost of cleaning was higher than the cost of energy loss.

Literature has shown some attempts to optimise the cleaning frequency of solar PV plants. Most of the studies have employed conventional and analytical methods in an attempt to optimise the cleaning cycle. However, it is evident that conventional optimisation techniques which have been mainly applied may be further improved in determining the reasonable cleaning cycle [20]. The current study focuses on the numerical formulation of an empirical soiling loss model for the dry season in Muzarabani, Zimbabwe. The model takes into cognisance the hourly incoming irradiance to determine the energy generated in each day. Further, the soiling loss model developed is dependent on the experimental measured daily soiling losses. The model recognises that different days have varying soiling rates. Such an approach is an improvement to the already existing optimisation models which either use an average annual value for power generation or an annual average soiling loss [21,22,25]. The present study recognises that the loss due to not cleaning is not a constant and it varies with the energy generated in the period of interest. The developed model is further optimised to determine the best cleaning interval of a solar PV plant. A metaheuristic approach is employed in the optimisation process due to the complexity of the problem and such an approach to optimising the cleaning frequency has not been widely explored.

Materials and methods

Experimental set up (determination of soiling loss factor)

An experimental set up was established at Muzarabani Rural District Council in Zimbabwe. The place is in a small residential area partly surrounded by an irrigation scheme, a natural conservative and a cattle ranch. The roads in the area are gravel roads with no pavement. The place is situated in the Dande low veld (Zambezi valley) which is characterised by high temperatures and prolonged dry periods. The area is generally characterised by a semi-arid climate. It has a relatively short rain season from November to March which is characterised by highly erratic rainfall of less than 650 mm per year. The temperatures can be as high as 36 °C. The experimental set up consists of 9 mono-crystalline JA solar panels with specifications at STC shown in Table 1. The solar panels were mounted at an angle of 20.5° facing North. The peak generation capacity of the solar PV system is 3.6 kW_p (see Fig. 1).

The solar system was run at full load every day from 8 AM to 4 PM. An average load of 2.5 kW was used on the system and a 40-kWh battery bank was incorporated. The set up made sure that almost all the generated power was used with some excess energy stored in the battery bank to act as a buffer when there is not enough solar energy. The installation set up was equipped with a Victron data logger with an online integration to store solar generation data. The set up was run for 7 months from 1 May 2019 to 31 November 2019 and the solar panels were cleaned once every month.

Determination of daily energy generated

The hourly solar energy, i.e. the global horizontal irradiance and beam irradiance incident on the solar system was freely obtained from SOLCAST (https://toolkit.solcast.com.au/historical). The relation developed by Liu and Jordan [26] was employed to determine the radiation on the tilted photovoltaic plane as shown by Eqs. 1 – 4 where I_T, I_b and I_d are hourly irradiance incident on a tilted plane, hourly beam irradiance and hourly diffuse irradiance, respectively. The values of the tilt factor for beam irradiance, diffuse irradiance and ground reflected irradiance are represented by R_b, R_d and R_r respectively. ω, ϕ, β and δ are respectively the hour angle, latitude, tilt angle and declination angle.

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \tag{1}$$

$$R_b = \frac{\sin(\phi+\beta)\sin\delta + \cos(\phi+\beta)\cos\delta\cos\omega}{\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega} \tag{2}$$

$$R_d = \frac{1+\cos\beta}{2} \tag{3}$$

$$R_r = \rho\frac{1-\cos\beta}{2} \tag{4}$$

The declination angle and the hour angle are given by Eqs. 5 – 6 where, n is the day number.

$$\delta = 23.34\sin\left[\frac{360}{365}(284+n)\right] \tag{5}$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \tag{6}$$

The solar energy expected to be generated by the solar system was calculated based on the incoming irradiance as outlined in Eq. 7 where P_a and W_p are the power generated by the solar PV array and the peak installed power, respectively. η_a and η_{ref} are respectively the PV array operating efficiency at ambient temperature T_a, and the reference PV array efficiency. After taking care of the temperature effects (governed by Eq. 8), the difference between the expected power generated and the actual power generated was recorded for each day under consideration where α is the temperature coefficient, T_{ref} is the reference temperature taken as 25°C. T_{NOCT} is the nominal operating cell temperature and is taken as 20°C while G_{NOCT} is taken as 800 W/m^2. The difference between the expected power generation (E_e) and the actual power generated (E_a) was attributed to soiling. The soiling ratio (R_s) was calculated for each day as shown in Eq. 9. The expected energy generation in each hour was calculated using Eq. 10.

$$P_a = \left(\frac{\eta_a}{\eta_{ref}}\right)\left(\frac{I_T}{1000}\right)W_p \tag{7}$$

$$\eta_a = \eta_{ref}\left[1-\alpha\left[T_a - T_{ref} + (T_{NOCT} - T_a)\frac{\overline{H_T}}{G_{NOCT}}\right]\right] \tag{8}$$

$$R_s = \frac{E_e - E_a}{E_e}\% \tag{9}$$

$$E_e = P_a \text{x1hour} \tag{10}$$

Problem formulation

A method developed by Abu-Naser [21] (Eq. 11) was adopted and modified to take effect of the daily variations in soiling losses where C_T is the total cost, N is the number of days between cleaning intervals, L_s, S_h, W_p and T are the soiling loss, mean annual peak sunshine hours, peak installed capacity and the energy tariff, respectively. C_c is the cost of cleaning made up of cost of labour, detergent and water.

$$C_T = \frac{365}{2}(N+1)L_s S_h W_p T + \frac{365}{N}C_c \tag{11}$$

In this study, cleaning was only considered for the dry season from May to November and hence 214 days were considered instead of 365 days for a full year. Further, the daily soiling rates and the daily energy generated were considered instead of the annual averaged values of soiling. The daily energy loss due to soiling is represented by the expression $(E_{e_i} - E_{a_i})$ in Eq. 12. The new empirical soiling loss model developed is shown in Eq. 12 where i = 1, 2, 3, …, n is the

Table 2
The electricity generation statistics.

	Month	E_e (kWh)	E_a (kWh)	E_e-E_a	% monthly Soiling	Daily averaged % soiling
1	May	885.21	807.00	78.21	8.84	0.29
2	June	792.00	710.00	82.00	10.35	0.35
3	July	788.00	693.00	95.00	12.06	0.40
4	August	801.00	685.00	116.00	14.48	0.48
5	September	894.00	768.00	126.00	14.09	0.47
6	October	870.00	754.00	116.00	13.33	0.44
7	November	865.00	750.00	115.00	13.29	0.44

i^{th} day. In this study, the cleaning cost (C_c) for the PV array used was taken as US$35 if a cleaning company was to be hired and the electricity tariff (T) was taken as US$0.09 which is a standard tariff for non-commercial energy use.

$$C_T = \frac{214}{N}C_c + 214T\sum_{i=1}^{n}\frac{1}{2}(N+1)(E_{e_i} - E_{a_i}) \tag{12}$$

Optimisation

An evolutionary computational intelligence algorithm called Particle Swarm Optimisation (PSO) was used to optimise the cost function outlined in Eq. 12. PSO is inspired by nature such as a school of fish looking for food. PSO was used because of the complexity of the problem due to variations in the quantity $E_{e_i} - E_{a_i}$for each day. The overall intention was to minimise the number of days between cleaning cycles (N). The operating principle of the algorithm is relatively simple with two main parameters which are velocity and position. A population of particles is initialised with random velocities $V_i^0$and positionsX_i^0which are evaluated against a cost function. As the computation progresses, the velocities and positions are updated according to the particles' own history as well as the history of the population. With a time step of k+1, the position and velocity will be outlined as shown in Eq. 13 and 14 [27] where, l_i^k is the i^{th} particle's best position and g^k is the global best position while ϕ_1 and ϕ_2 represent the global and local accelerations. a_l and a_g are local and global acceleration terms, ω is the inertia, r_1 and r_2 are random numbers, I is a scalar quantity for the time step. $\phi_1 = r_1 a_g$, $\phi_2 = r_2 a_l$, r_1, r_2 $\rightarrow$ U (0,1) and ω, a_g, a_l are all real numbers.

$$V_i^{k+1} = \omega V_i^k + \phi_1.I.\left(g^k - X_i^k\right) + \phi_2.I.\left(l_i^k - X_i^k\right) \tag{13}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1}.I \tag{14}$$

Results and discussions

Power generation and soiling

The daily power generated from 1 May 2019 to 30 November 2019 was recorded and the difference between the energy generated and the expected energy was noted. Average monthly values of the expected energy E_e and the actual energy E_a were established as shown in Table 2. As the PV array was cleaned at the beginning of every month, there was more energy generated at the beginning of each month and the amount of energy generated reduced with each passing day until another cleaning cycle was performed. Some light showers experienced in the month of August had a negative influence on the energy generated. The rain was less than 5 mm and hence could not help in the natural cleaning process but rather caused more soiling with more dust sticking onto the solar panels. Such a scenario is also similar to the effect of dew and humidity as reported in other studies [28,29].

The study revealed a daily average soiling rate of 0.41 % and an average value of solar energy on a tilted plane of 700 W/m^2. The soiling rate of 0.41 % correlates well with studies done in the region in areas with similar climatic conditions [11]. The average energy generated each day was found to be 24.6 kWh at average peak sunshine hours of 6.5 hours. The results also revealed characteristic average daily and monthly energy losses of 3.47 kWh and 104.03 kWh respectively. However, the study revealed that the daily losses varied from day to day although the daily soiling losses were not too different with successive days. The daily average monthly percentage losses are shown in Table 2 with 0.29 % in the month of May being the least and 0.48 % in the month of August being the maximum for the period under study (See Table 2). However, the month of September had the greatest loss of energy in terms of kWh.

The differences in daily soiling losses is attributed to the daily differences in weather conditions including wind speed, wind direction, precipitation and cloud cover which is a factor in dew formation. The month of August experienced the maximum percentage loss of 14.48 %. This is due to the violent wind flows and relatively high wind speeds experienced in this month. Such a phenomenon result in high deposition rates and hence the soiling will be more. Similar results were reported for a study under similar climatic conditions in South Africa [11]. The month of May experienced the least soiling

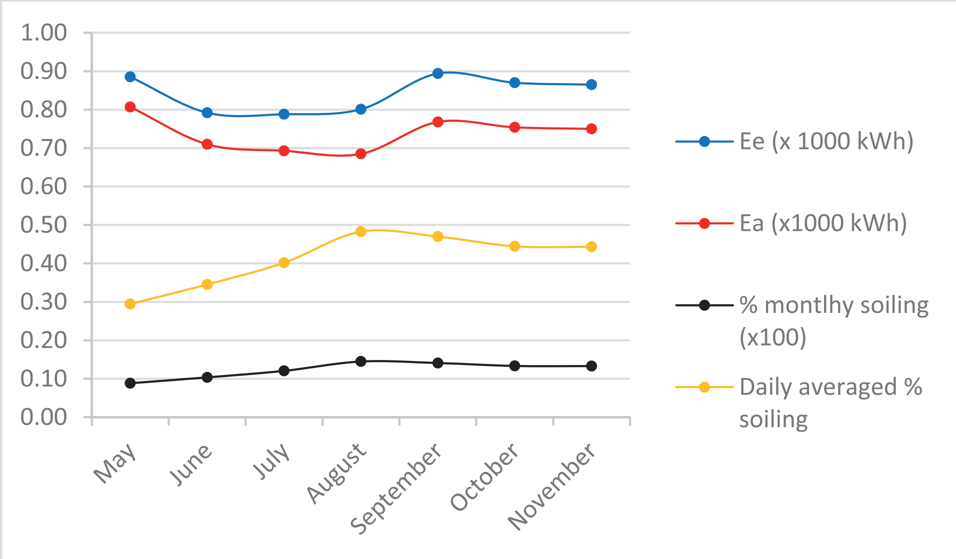

Fig. 2. Soiling and energy generation.

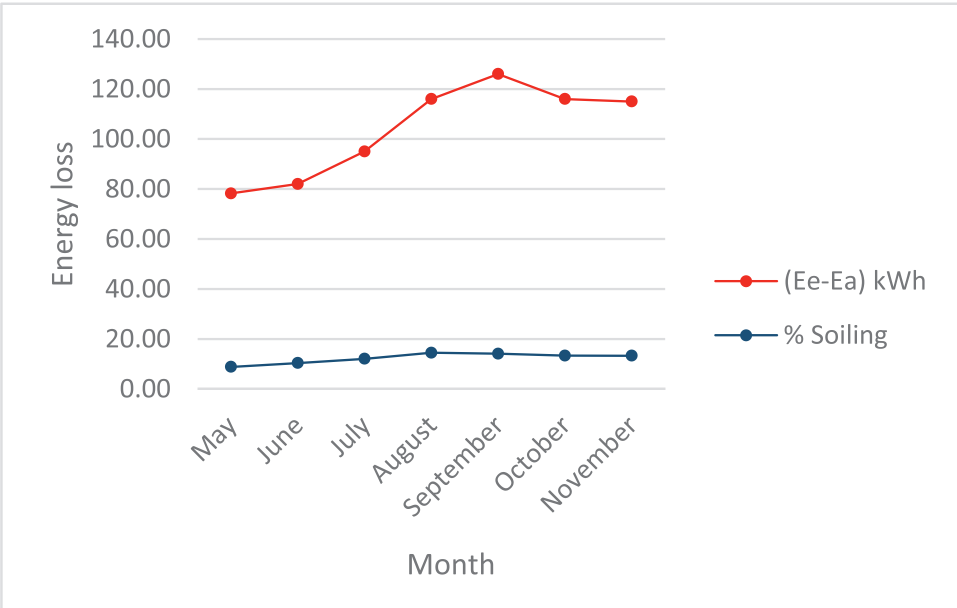

Fig. 3. Energy loss.

of 8.84 % because it is the beginning of the dry season and hence extreme dry conditions are not experienced during this period.

The soiling and energy generation profiles are shown in Fig. 2. The expected energy generation was always higher than the actual energy generated. Having considered the effects of temperature, the difference between expected and actual energy generated was attributed to soiling.

Optimisation

Optimisation was done in PSO to minimise the number of days between cleaning events. The total cost minimised was the cost of energy loss and the cost of cleaning. The energy cost used was US$0.09 while the cost of cleaning was taken as US$35 per each manual cleaning event. The solution converged after 93 iterations as shown in Fig. 4. Optimisation resulted

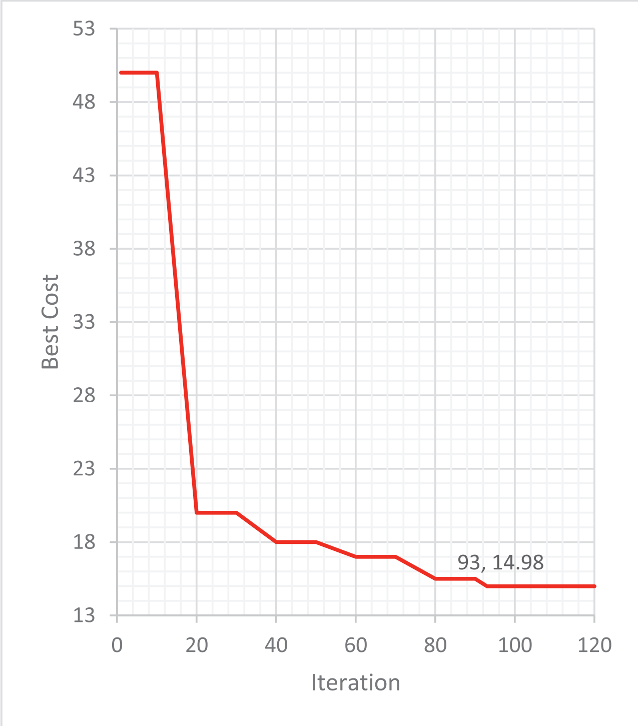

Fig. 4. Diagram for solution convergence.

in an optimised cleaning cycle of 14.98 days and hence it was noted that the optimal cleaning cycle for the location under study is every 15 days. Such a result is expected in such a place in a semi-arid location when compared to similar locations in desert environments [20].

When compared to other studies in the region, the cleaning frequency is relatively high. Studies done in Kalkbult, South Africa reported no requirement for cleaning owing to the high cost of cleaning compared to the energy gain [24]. Such a difference is attributed to several factors. The soiling characteristics of these two areas are different owing to the different land uses. In Muzarabani, the surrounding area is used for agricultural activities enabled by the available irrigation system. Furthermore, the roads in the area are gravel roads. Such a phenomenon accelerates the soiling rate of the solar PV plant. Moreover, an important factor used in optimising the cleaning frequency is the cost of energy which is completely different in the two countries.

Conclusions

In this study, the influence of varying daily soiling rates was considered in minimising the number of days between successive cleaning intervals. An empirical soiling loss model was developed and optimised to reduce the cleaning cycles in a 3.6 kW_p power plant. The results showed that soiling was different for each month and, also daily variations were experienced due to the influence of varying weather conditions such as wind speed, direction and humidity. The study showed that the soiling rates were different with each day and month and hence soiling cannot be taken as uniform throughout the year. The results showed that it was necessary to clean once in 15 days in order to minimise the losses associated with both frequent cleaning as not cleaning.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding information

The authors are grateful for the assistance from the University of South Africa in the course of this research.

References

[1] N.M. Haegel, et al., Terawatt-scale photovoltaics: trajectories and challenges, Science 356 (6334) (Apr. 2017) 141–143, doi:10.1126/science.aal1288.

[2] T. Alquthami, K. Menoufi, Soiling of photovoltaic modules: comparing between two distinct locations within the framework of developing the photovoltaic soiling index (PVSI), Sustainability 11 (17) (Aug. 2019) 4697, doi:10.3390/su11174697.

[3] S. Akbar, T. Ahmad, Enhance and maintain efficiency of solar panel using auto cleaning system, IJEW 6 (05) (May 2019) 159–163, doi:10.34259/ijew.19.605159163.

[4] T. Sarver, A. Al-Qaraghuli, L.L. Kazmerski, A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches, Renew. Sustain. Energy Rev. 22 (Jun. 2013) 698–733, doi:10.1016/j.rser.2012.12.065.

[5] B. Guo, W. Javed, B.W. Figgis, T. Mirza, Effect of dust and weather conditions on photovoltaic performance in Doha, Qatar, First Workshop Smart Grid Renew. Energy (SGRE (2015) 1–6 2015Mar., doi:10.1109/SGRE.2015.7208718.

[6] Bahaj Alghamdi, Blunden, Wu, Dust removal from solar PV modules by automated cleaning systems, Energies 12 (15) (Jul. 2019) 2923, doi:10.3390/en12152923.

[7] S. Toth, et al., Soiling and cleaning: initial observations from 5-year photovoltaic glass coating durability study, Solar Energy Mater. Solar Cells 185 (Oct. 2018) 375–384, doi:10.1016/j.solmat.2018.05.039.

[8] S. Ghazi, A. Sayigh, K. Ip, Dust effect on flat surfaces – a review paper, Renew. Sustain. Energy Rev. 33 (May 2014) 742–751, doi:10.1016/j.rser.2014.02.016.

[9] H. Lu, L. Lu, Y. Wang, Numerical investigation of dust pollution on a solar photovoltaic (PV) system mounted on an isolated building, Appl. Energy 180 (Oct. 2016) 27–36, doi:10.1016/j.apenergy.2016.07.030.

[10] S. Pulipaka, R. Kumar, Analysis of soil distortion factor for photovoltaic modules using particle size composition, Solar Energy 161 (Feb. 2018) 90–99, doi:10.1016/j.solener.2017.11.041.

[11] D.J. Griffith, L. Vhengani, M. Maliage, Measurements of mirror soiling at a candidate CSP site, Energy Procedia 49 (2014) 1371–1378, doi:10.1016/j.egypro.2014.03.146.

[12] V.S. Saravanan, S.K. Darvekar, Solar photovoltaic panels cleaning methods a review, Int. J. Pure Appl. Math. 118 (24) (2018).

[13] M. Naeem, G. TamizhMani, Cleaning frequency optimization for soiled photovoltaic modules, 2015 IEEE 42nd Photovolt. Spec. Conf. (PVSC) (Jun. 2015) 1–5 New Orleans, LA, doi:10.1109/PVSC.2015.7355972.

[14] W. Li, et al., Broadband antireflective and superhydrophobic coatings for solar cells, Mater. Today Energy 12 (Jun. 2019) 348–355, doi:10.1016/j.mtener.2019.03.006.

[15] M. Fathi, M. Abderrezek, M. Friedrich, Reducing dust effects on photovoltaic panels by hydrophobic coating, Clean. Techn. Environ. Policy 19 (2) (2017) 577–585, doi:10.1007/s10098-016-1233-9.

[16] G.G. Jang, D.B. Smith, G. Polizos, L. Collins, J.K. Keum, D.F. Lee, Transparent superhydrophilic and superhydrophobic nanoparticle textured coatings: comparative study of anti-soiling performance, Nanoscale Adv. 1 (3) (Mar. 2019) 1249–1260, doi:10.1039/C8NA00349A.

[17] S. Patil and H. H. Mallaradhya, “Design and implementation of microcontroller based automatic dust cleaning system for solar panel,” Int. J. Eng. Res. Adv. Technol., vol. 02, p. 4.

[18] M. Al-Housani, Y. Bicer, M. Koç, Assessment of various dry photovoltaic cleaning techniques and frequencies on the power output of CdTe-type modules in dusty environments, Sustainability 11 (10) (May 2019) 2850, doi:10.3390/su11102850.

[19] R. Conceição, H.G. Silva, L. Fialho, F.M. Lopes, M. Collares-Pereira, PV system design with the effect of soiling on the optimum tilt angle, Renew. Energy 133 (Apr. 2019) 787–796, doi:10.1016/j.renene.2018.10.080.

[20] Y. Jiang, L. Lu, H. Lu, A novel model to estimate the cleaning frequency for dirty solar photovoltaic (PV) modules in desert environment, Solar Energy 140 (Dec. 2016) 236–240, doi:10.1016/j.solener.2016.11.016.

[21] M. Abu-Naser, Solar panels cleaning frequency for maximum financial profit, OJEE 06 (03) (2017) 80–86, doi:10.4236/ojee.2017.63006.

[22] R. Karkee, S. Khadka, Closer approximation to optimize solar panels performance with cleaning cycle: a follow-up, OJEE 08 (04) (2019) 166–178, doi:10.4236/ojee.2019.84010.

[23] A. Ullah, A. Amin, T. Haider, M. Saleem, N.Z. Butt, Investigation of soiling effects, dust chemistry and optimum cleaning schedule for PV modules in Lahore, Pakistan, Renew. Energy 150 (May 2020) 456–468, doi:10.1016/j.renene.2019.12.090.

[24] T.A. Solend, Cleaning schedule based on soiling effects on photovoltaics in Kalkbult, South Africa, 2017 MSc Thesis, Norwegian University of Life Sciences.

[25] R.K. Jones, et al., Optimized cleaning cost and schedule based on observed soiling conditions for photovoltaic plants in central Saudi Arabia, IEEE J. Photovoltaics 6 (3) (May 2016) 730–738, doi:10.1109/JPHOTOV.2016.2535308.

[26] B. Liu, R. Jordan, Daily insolation on surfaces tilted towards equator, ASHRAE J.; (United States) 10 (Oct. 1961) Accessed: Apr. 03, 2020. [Online]. Available https://www.osti.gov/biblio/5047843-daily-insolation-surfaces-tilted-towards-equator .

[27] J.L. Fernández Martínez, E. García Gonzalo, The generalized PSO: a new door to PSO evolution, J. Artif. Evol. Appl. (2008) https://www.hindawi.com/journals/jaea/2008/861275/. (accessed Apr. 08, 2020).

[28] T. Sarver, A. Al-Qaraghuli, L.L. Kazmerski, A comprehensive review of the impact of dust on the use of solar energy: history, investigations, results, literature, and mitigation approaches, Renew. Sustain. Energy Rev. 22 (2013) 698–733, doi:10.1016/j.rser.2012.12.065.

[29] H.K. Elminir, A.E. Ghitas, R.H. Hamid, F. El-Hussainy, M.M. Beheary, K.M. Abdel-Moneim, Effect of dust on the transparent cover of solar collectors, Energy Conver. Manag. 47 (18–19) (2006) 3192–3203, doi:10.1016/j.enconman.2006.02.014.