Modeling of Soiling Derating Factor in Determining Photovoltaic Outputs

Wan Juzaili Jamil, Hasimah Abdul Rahman, *Member, IEEE*, Sulaiman Shaari, and Mohd Khairunaz Mat Desa, *Member, IEEE*

***Abstract*—The study of the effect of soiling on photovoltaic (PV) system performance is a crucial issue judging from numerous research publications. The reduction in the PV system performance is because of soiling that differs from one climatic region to another. In this research, the power losses due to soiling of the PV systems in Malaysia based on the calculation of a dirt derating factor (f_{dirt}) were determined. A new mathematical model to correlate f_{dirt} and the PV module area was developed based on the regression analysis from a site data location. The findings indicate that the effect of soiling reduces the PV systems output power at an average of 26.22% at Setiu over a period of 12 months. From this study also, a new mathematical model was created for f_{dirt} forecasting in the research site. Uniquely, this mathematical model can do the prediction by only known PV module area or size as the independent variable, much simpler than using the multivariables equation.**

***Index Terms*—Loss, mathematical model, performance, PV system, soiling.**

I. Introduction

SOLAR energy is one of the most promising renewable energy resources. In order to harvest the energy from solar radiation, photovoltaic (PV) systems have been developed as the medium of energy conversion. The PV modules are responsible to convert solar irradiance (solar energy) into electrical energy. Hence, the module needs to be placed outdoors, which will expose it to the either natural or urbanized environment. In this condition, it will be affected by environmental factors that may reduce its output and reliability. The factors such as fluctuation of global irradiance, adverse weather conditions, local air pollution, ambient temperature, and soiling will affect the output of the PV system [1]–[4]. Soiling or settlement of dust on PV module's surface is a very common issue that affects the PV module output directly. Fig. 1 indicates a serious soiling phenomenon of a PV array under the atmospheric condition. In this figure, the PV module is almost covered by soiling.

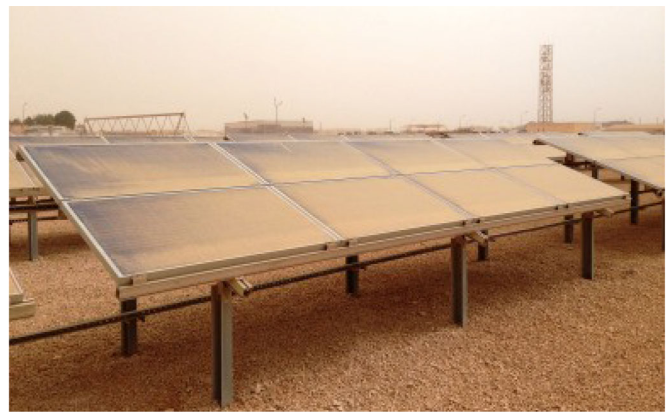

Fig. 1. Soiled PV array under the atmospheric condition [5].

Soiling is formed from the accumulation of dust over a surface. Dust particles from the air, usually carried by the wind [1], [4], [6]–[8], will settle on any surface due to gravitation. These particles will settle down and their density will keep increasing over time with the addition of other airborne dust particles settling in the same place. Hence, this will create a dust layer or "soiling." The presence of soiling reduces the absorption of irradiation for electricity conversion. Thus, this will reduce the energy output and the overall performance of the PV system.

This problem needs to be considered prior to and after the installation of the PV system since it impacts upon the return of investment for the owner, investor, or the user. Therefore, this research is undertaken to address the significant problem of soiling. The intention is to study the impact of soiling on a PV system's performance in a highly humid tropical country, Malaysia (as referred to Köppen–Geiger's world maps of climate classification [9]), where the issue of soiling is not being paid enough attention and where comprehensive study is lacking. In the perspective of soiling, previous studies focused on the estimation of the impact of soiling on PV systems by comparing the PV system's yield when the PV module is clean and when the PV module is dusty [10]–[12]. And most of the studies are performed in temperate and arid climate regions where the seasonal changes are predictable, allocating the meteorological

Manuscript received March 3, 2020; revised May 12, 2020; accepted June 13, 2020. Date of publication July 1, 2020; date of current version August 20, 2020. This work was supported by the Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia through the awarded Tier 1 Grant (vote no: Q.J13000.2509.07H54). *(Corresponding author: Wan Juzaili Jamil.)*

Wan Juzaili Jamil was with the Centre of Electrical Energy Systems, Institute of Future Energy, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia. He is now with the School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal 14300, Malaysia (e-mail: rockzzlee@yahoo.com).

Hasimah Abdul Rahman was with the Centre of Electrical Energy Systems, Institute of Future Energy, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia (e-mail: hasimah@fke.utm.my).

Sulaiman Shaari is with the Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam 40450, Malaysia (e-mail: solarman1001@gmail.com).

Mohd Khairunaz Mat Desa is with the School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal 14300, Malaysia (e-mail: khairunaz@usm.my).

Color versions of one or more of the figures in this article are available online at https://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JPHOTOV.2020.3003815

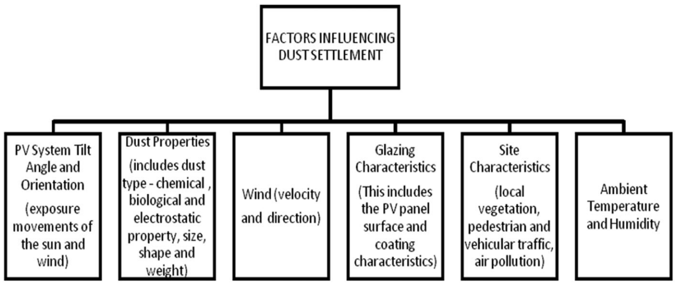

Fig. 2. Factors affecting the dust accumulation [1].

or seasonal variability study on the impact of soiling [10], [13], [14]. However, the Malaysian climate is also unique and apparently different from the other, mainly arid, regions where most PV systems have been installed.

Although Malaysia is located in the equatorial and tropical zone, the weather can be unpredictable. This is mostly influenced by the flow of monsoon winds [15] from the northeast and the southwest part of the country. Rain and dry periods alternate on each other regardless of time. This makes the Malaysian climate unique when compared to other tropical countries that have notable and predictable seasonal changes, such as Thailand, Myanmar, and Indonesia [16].

This study calculated the dirt derating factor of the selected PV system in Malaysia and quantified its yield reduction due to soiling over a one-year period through a PV system output power data observation. This study also developed a mathematical model of dirt derating factor versus PV module area to determine the correlation between them. Hopefully, the findings from this research will provide useful information for the PV generator plant owners, industrial players, or other researchers who are considering the deployment of a PV system, the maintenance planning, and the forecasting of a PV system's output with regard to soiling in the Malaysian climate.

II. Soiling Origin and Its Impact on the PV Module's Performance

Soiling occurs from the accumulation of dust that settles on a surface. Dust on the hand is a term commonly applied to solid particles having diameter less than 500 μm [1]. Factors influencing dust settlement on PV modules are represented in a framework by Mani and Pillai [1] in Fig. 2.

In review articles [1], [3], [6], and [17], lots of researchers have proven that soiling problem significantly degrades the PV system performance and the degree of degradation severity is site dependent. From these reviews, it can be seen that most of soiling studies were performed in countries with extreme dry and wet seasons where the soiling effect on the PV system's performance can be observed clearly. However, there are very few published studies available on the effect of soiling under tropical climates such as Malaysia that have high humidity, and mixed wet and dry weather throughout the year, as mentioned by Sulaiman *et al.* [18]. Therefore, this study is performed to estimate the soiling loss from a commercial PV system in a fully humid tropical climate region in Malaysia.

III. Dirt Derating Factor

In estimating the output power or yield of a PV system, there are other factors to be considered (PV module efficiency, inverter efficiency, and cable loss) as it may affect the yield. Usually in an estimation equation for PV system's output power or energy, these factors are included together as other variables or just constants. In an example given in [19], the estimation equation used is

$$E_{\mathrm{PV}} = A \times E_{\mathrm{sun}} \times \eta_{\mathrm{PV}} \times \eta_{\mathrm{inv}} \times \xi_{\mathrm{cable}} \quad (1)$$

where E_{PV} is the estimated PV system's energy yield, A is the area of the PV module, and E_{sun} is daily solar irradiation. The multiplication of both parameters determines the amount of PV system's energy yield. Meanwhile, η_{PV}, η_{inv}, and ξ_{cable}, which are the efficiency of PV module, efficiency of inverter, and cable loss, respectively, are other factors in per unit value that affects the energy yield $(A_{\mathrm{PV}} \times E_{\mathrm{sun}})$. They can also be presented in percentage value by multiplying the per unit value with 100. These derating factors are included in this equation as a concern on the reduction of the PV system's yielded energy caused by any of them. If there are more derating factors to be added in, it can also be included in (1).

Therefore, considering the atmospheric condition, the heat absorbed by the PV module and soiling that reduces the output energy of a PV system can also be included in (1). Equation (1) can be rewritten as

$$E_{\mathrm{PV}} = A_{\mathrm{PV}} \times E_{\mathrm{sun}} \times \eta_{\mathrm{PV}} \times \eta_{\mathrm{inv}} \times \xi_{\mathrm{cable}} \times f_{\mathrm{temp}} \times f_{\mathrm{dirt}} \quad (2)$$

where f_{temp} is the module heating derating factor due to heat absorbed and f_{dirt} is dirt derating factor due to soiling effect. In most cases, f_{dirt} is an estimated value gain from (2). By knowing the other parameters value in (2), f_{dirt} can be calculated. From a study in [20]–[22], f_{dirt} is described as an empirically derived factor to indicate the reduction of PV system performance due to soiling.

Other than that, the estimation of f_{dirt} can also be performed by comparing the energy yield or output of a PV system for the cleaned PV module condition and the dusty module condition. This has been carried out in the studies in [20], [21], [23]–[26]. In these studies, the estimation of f_{dirt} is done through the monitoring and output power or energy yield record of the following.

1) PV system on a certain period where the PV modules were left unclean and dusty. And they recorded it again for another period when the PV modules were regularly cleaned.
2) PV system on a certain dry period without rain. And they recorded it again during the rainy season where the PV modules were naturally cleaned.
3) Two identical PV systems on the same observation period. One of them was cleanly maintained, whereas the other was left dusty.

The difference between PV modules yield found within the record of the cleaned PV modules condition and the dusty PV modules condition was observed, and from these, f_{dirt} was estimated.

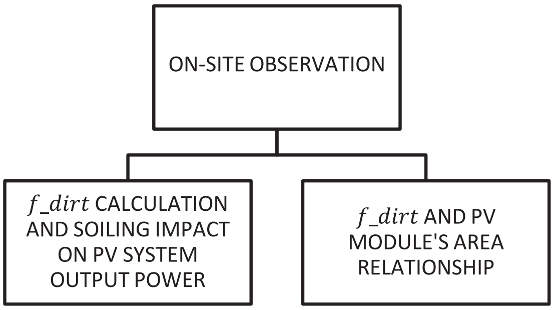

Fig. 3. Research tasks during on site's PV system's performance monitoring.

In the literature source, there are several more studies performed in the interest related to f_{dirt}. However, soiling loss estimation through the relationship of f_{dirt} and PV module area or size is still absent from the current literature. Therefore, one of the objectives in this study is to develop a new mathematical model to correlate f_{dirt} and the PV module area. The outcome from this objective will be useful for soiling loss forecasting in the studied site.

IV. Methodology

In this research, there are two tasks that were performed during the site observation. Fig. 3 indicates the tasks executed during the research.

The on-site observation of the PV system was carried out by monitoring the trend of the PV system output power and its degradation due to soiling over a period of 12 months. The observation was made on a 2.5 MW_p grid connected PV system located in Setiu, Malaysia (Latitude = 5.5167° North; Longitude = 102.7667° East) owned by Synergy Generated Sdn. Bhd (Company registration no: 918256-K).

The PV system is located near foothill and surrounded by small trees. The main road is about 300 m from this site and the traffic activity is not heavy. There is an online monitoring system for data collection and performance monitoring installed for the PV system. This facility that was constructed in 2014 and first operated on January 1, 2015 is a well-maintained plant where the PV modules are cleaned once every two months.

The modules are polycrystalline silicon being mounted about 1.5 m from the ground and tilted at 5° from the horizontal facing south. The modules' temperature coefficient value γ_{pmp} and PV module mismatch derating factor f_{mm} from the manufacturer specification datasheet are −0.4%/°C and 97% (as during factory test) each.

In Table I, some of the data are taken from the observation made at the PV system location.

In this study, the observation involves f_{dirt} calculation, the determination of PV system's output power loss due to soiling, the correlation analysis between PV module's area versus f_{dirt}, and the regression of that correlation to develop new mathematical model of f_{dirt}. The observations and analysis were performed based on the recorded plant data. The methodology will be elaborated further in the next section.

TABLE I
PV System Location Observation Data

Capacity	2.5 MW
Year of the data taken	2015
Location	Setiu, Terengganu, Malaysia
Climate	Equatorial (fully humid tropical)
Coordinate	(Latitude. = 5.5167° North ; Longitude. = 102.7667° East)
PV modules quantity	8,640 units of 300 W_p module
PV module's size	1.8 m² for each module
PV modules model code	HSL72P6-PB-4-300T (Manufacturer: Hanwha Coporation)
Height of Modules mounting from the ground	1.5 meter (5° tilted)
Cleaning schedule	Once every two months
Surrounding environment	Near foothill and surrounded by small trees. About 300 meters from main road. No heavy traffic.
Average peak sun hour period	4.69 hours

A. f_{dirt} *Calculation and Soiling Impact Analysis on PV System Performance*

The main objective for this study is to retrieve the data from the system data logger for PV system's output power observation and to calculate the system's f_{dirt}. The value of f_{dirt} (%) can be calculated using [27]

$$E_{\text{sys}} = P_{\text{array\_stc}} \times \text{PSH}_{\text{period}} \times f_{\text{temp}} \times f_{\text{dirt}} \times f_{\text{mm}} \times \xi_{\text{cable}} \times \eta_{\text{inv}} \times K_{\text{aging}} \quad (3)$$

where $P_{\text{array\_stc}}$ is the total PV array capacity ($\text{k}W_p$), $\text{PSH}_{\text{period}}$ is the peak sun hours, f_{temp} is the derating factor due to module temperature, f_{mm} is the module mismatch derating factor given by the manufacturer, ξ_{cable} is the losses from cable resistance, η_{inv} is the dc–ac inverter efficiency also given by the manufacturer, K_{aging} is the derating factor due to PV system's aging, and finally, E_{sys} is the predicted system energy yield. In this case, as the energy was already known from the data logger system, E_{sys} is counted as E_{yield}. Hence, from (3)

$$f_{\text{dirt}} = \frac{E_{\text{yield}}}{P_{\text{array\_stc}} \times \text{PSH}_{\text{period}} \times f_{\text{temp}} \times f_{\text{mm}} \times \xi_{\text{cable}} \times \eta_{\text{inv}} \times K_{\text{aging}}}. \quad (4)$$

The value of f_{temp} can be obtained using [27]

$$f_{\text{temp}} = 1 + \frac{\gamma_{\text{pmp}}}{100}\left(T_{\text{modules}} - 25\right) \quad (5)$$

where γ_{pmp} is the module's temperature coefficient value for output power at maximum power point, P_{mp} given in % (of power reduction) per degree Celsius by the module's manufacturer. f_{dirt} can be calculated from (4) by using the available data from PV system's data logger as the empirical value. The value of f_{dirt} indicates the percentage of output power reduction due to soiling.

However, if the instantaneous ac output power of the PV system, P_{AC} is used to replace E_{yield}; hence, (4) is rewritten as [27]

$$f_{\text{dirt}} = \frac{P_{\text{AC}}}{P_{\text{array\_stc}} \times \text{PSF} \times f_{\text{temp}} \times f_{\text{mm}} \times \xi_{\text{cable}} \times \eta_{\text{inv}} \times K_{\text{aging}}} \quad (6)$$

where PSF is the peak sun factor, which is obtained by dividing the instantaneous value of solar irradiance (from the data logger) in W/m^2 with 1000 W/m^2. In this case, P_{AC} value is taken as an instantaneous value at solar irradiance of 1000 W/m^2. Therefore, by dividing solar irradiance of 1000 W/m^2 with 1000 W/m^2, PSF becomes 1. The reason for this is to mitigate the data inaccuracy during the observation using the average daily P_{AC} value as there was only one pyranometer to measure the irradiance for 8640 units PV module, which was very wide for pyranometer-modules' ratio. The ratio of pyranometer reading to the PV module's area is too big, and may cause data inaccuracy if the daily average value of P_{AC} is used. By using the instantaneous P_{AC} value at the irradiance of 1000 W/m^2, the pyranometer provided the most accurate reading as the sun is mostly on its peak location, its light during that condition covering all the observed PV modules. The condition of sunlight at irradiance of 1000 W/m^2 (noon) is different than in the morning and evening, which experiences the increment and reduction of solar irradiance in the average daily P_{AC} data. The approach taken in this research is different from a research by Deceglie *et al.* [28], who used average PV modules power output value in the analysis and their observed modules quantity were much smaller, but having the same purpose, to eliminate the inaccuracy in data collection. Meanwhile, f_{mm}, ξ_{cable}, η_{inv}, and K_{aging} are the same variables as defined in (3). However, the values for these were not available at the research site. Usually, their value are constant throughout the measurement [27]; hence, the parameters f_{mm}, ξ_{cable}, η_{inv}, and K_{aging} can be combined together as β. β is still reflected in the derating factors to be included in (6). Therefore, (6) becomes

$$f_{\text{dirt}} = \frac{P_{\text{AC}}}{P_{\text{array\_stc}} \times f_{\text{temp}} \times \beta}. \quad (7)$$

As for the $P_{\text{array\_stc}}$ value, this parameter is also a constant and it is obtainable. P_{AC} is varied during the measurement and this value is also obtainable directly from the PV system's data logger. Plus, f_{temp} is calculated using (5). The value for $(f_{\text{temp}} \times \beta)$ is obtained through data regression between two parameters. In (7), $P_{\text{array\_stc}}$ and P_{AC} is obtained directly, but f_{temp} according to (5) is a linear function of T_{modules}. T_{modules} data are also obtainable directly from data logger. Therefore, $(f_{\text{temp}} \times \beta)$ can be solved through the linear function data regression using IBMs SPSS software between f_{temp} and T_{modules}.

Hence, from the data regression

$$(f_{\text{temp}} \times \beta) = 1.112 - 0.004T_{\text{module}}. \quad (8)$$

TABLE II
PV Developed f_{dirt} Calculation Table From the Processed Data

Date	P_{AC} (kW)	P_{array_stc} (MW)	$T_{modules}$ (°C)	f_{dirt} (%)
16.02.2015	2,099.304	2.592	54.1670	8.311186
17.02.2015	2,047.847	2.592	56.0354	9.795406
18.02.2015	1,951.960	2.592	56.3718	13.88677
19.02.2015	2,002.556	2.592	53.0154	12.99047

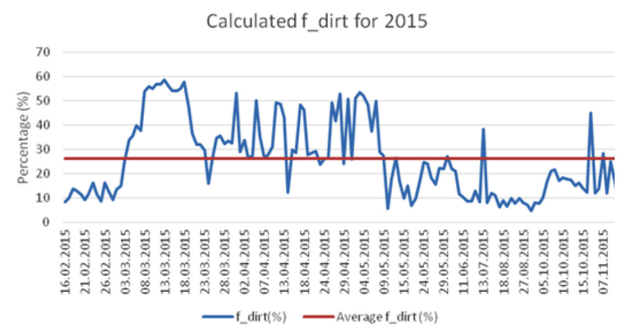

Fig. 4. Historical diagram of the calculated PV system's f_{dirt}.

Therefore, to calculate f_{dirt} for the PV system, following equation is used:

$$f_{\text{dirt}} = \frac{P_{\text{AC}}}{P_{\text{array\_stc}} \; (1.112 - 0.004T_{\text{module}})}. \quad (9)$$

From the studied site, the required data for f_{dirt} calculation was collected and then inserted into a Microsoft Excel table as shown in Table II. The values for f_{dirt} are then calculated using (9).

Finally, by filling up Table II in Microsoft Excel, the historical diagram of calculated f_{dirt} from the site was obtained and will show the trend of f_{dirt} and power loss due to soiling for a one-year observation. In Table II, it is shown the daily increment of f_{dirt} from 8.31% to 12.99%. This increment can happen due to the rapid soiling accumulation when the PV modules are left unclean for certain periods without any precipitation occurrence. And for a large area of PV modules like this, rise of daily f_{dirt} can be significant as soiling can disperse everywhere within the modules' area creating module mismatch losses [1].

B. *Regression of a Mathematical Model*

In this study, the regression analysis was performed with IBM SPSS software. The analysis based on Pearson's correlation coefficient [29], [30] is carried out to correlate f_{dirt} and the area or size of PV modules in a mathematical model, an equation.

V. Data Analysis and Result Discussion

A. *f_{dirt} Calculation and Soiling Impact Analysis on PV System Performance*

The historical diagram of f_{dirt} calculated for the studied site is obtained as in Fig. 4.

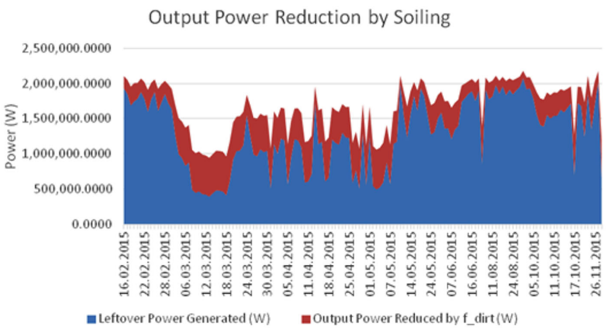

Fig. 5. Portion of PV system's output power reduction by soiling in Watts.

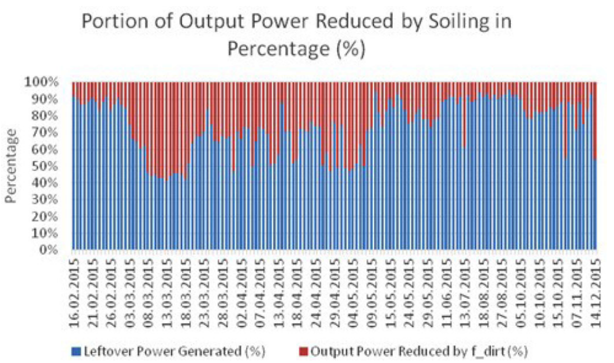

Fig. 6. Portion of PV system's output power reduction by soiling as a percentage.

According to Fig. 4, the calculated f_{dirt} values obtained here are ranged from 4.86% to 58.67% with the average value of 26.22% for the whole observed year. Fortunately, in representing the expected soiling, the calculated f_{dirt} quantification shows that the plant yield reduction due to soiling can be severe, moderate and minor effects on the PV system's performance during the observed year. To be clear on this, another historical diagram to indicate the portion of the system's yield reduction from soiling was developed in Fig. 5. Besides, another historical diagram in percentage form to indicate the portion of the system's yield reduction from soiling was developed in Fig. 6.

In Fig. 5, the graph is intended to display the portion of output power reduced by soiling (in red) in comparison with the leftover output power from the PV system after deducting the soiling loss (in blue). Meanwhile, in Fig. 6, the graph shows the comparison of portion of PV system's output power reduction due to soiling from the overall generated output power in percentage form. From both figures, it shows that the impact of soiling for this plant was severe and the portion of the power reduction due to soiling can be more than 50% for a significant amount of time. This means that, sometimes, half of the whole system's output power is reduced by soiling.

B. *Modeling of* f_{dirt} *and PV Module's Area Relationship*

For the studied PV system, the available data from research site enabling one correlation study between f_{dirt} and area. In this case, the area is that of the PV modules. There were 2700 out of 8640 total units PV modules involved in this study. Each of the PV module's effective area is 1.8 m^2. The study is carried out to determine the influence of the area or size of the PV modules on f_{dirt}. For this analysis, (9) was applied to calculate f_{dirt} using the data measured at solar irradiance of 1000 W/m^2, which has been normalized from the various random selected sample data. Fig. 7 shows the scatter plot for f_{dirt} and area relationship developed in Microsoft Excel.

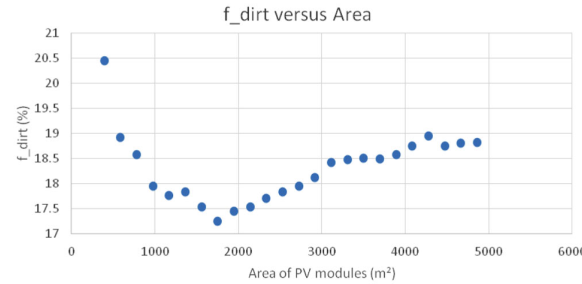

Fig. 7. Scatter plot of f_{dirt} and area correlation.

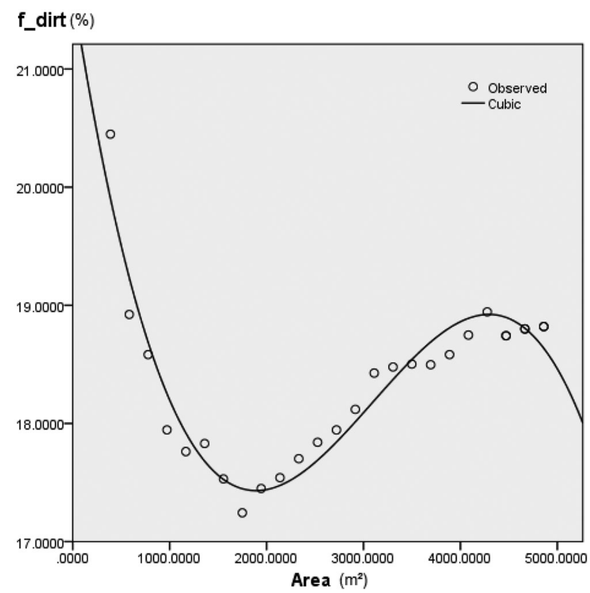

Fig. 8. Curve fitting for f_{dirt} and area data regression.

In Fig. 7, the scatter plot has a pattern similar to a logarithmic curve, but only after the eighth dot (from the left) until the last one, the curve tends to go upward and then becoming almost stagnant toward the end. However, judging from the scatter plot overall pattern, it is hard to get good result of the regression analysis. However, the regression analysis is still needed to be carried out to see how significant the relationship of f_{dirt} and area.

The curve fitting analysis is performed to select the best regression that suits the pattern and represents the mathematical relationship whether it is linear, inverse, logarithmic, quadratic, cubic, exponential, or spline interpolation. Fig. 8 and Table III show the best curve-fitting analysis results from IBMs SPSS.

According to the results in Table III, the cubic interpolation curve fits the data accordingly. The relationship of f_{dirt} and area are studied based on the r^2 value [29], [30]. r^2 is obtained as 0.92,

TABLE III
SPSS Curve Fitting Result for $f_{\rm dirt}$ and Area Data Regression

Model Summary				
Regression type	R	R Square	Adjusted R Square	Std. Error of the Estimate
Cubic	.959	.920	.908	.210
The independent variable is area				

TABLE IV
Cubic Regression Analysis Result for the $f_{\rm dirt}$ and Area Relationship

ANOVA					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	10.111	3	3.370	76.618	.000
Residual	.880	20	.044		
Total	10.991	23			

Coefficients					
	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Area	-.005	.000	-10.616	-12.765	.000
Area ** 2	2.047E-006	.000	21.914	11.387	.000
Area ** 3	-2.224E-010	.000	-11.384	.	.
(Constant)	21.703	.271		80.152	.000

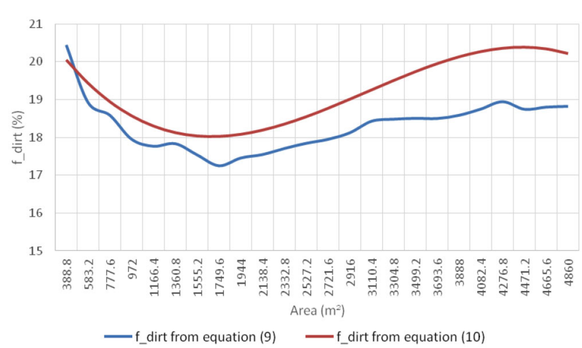

Fig. 9. Comparison of $f_{\rm dirt}$ ratio calculated from (9) and from cubic regression equation (10).

which is close to 1 [31]. Table IV indicates the cubic function regression results using IBMs SPSS.

From the result stated in Table IV, the equation that relates $f_{\rm dirt}$ and area is

$$f_{\rm dirt} = 21.703 - 0.005\ \text{Area} + 0.000002047\ \text{Area}^2 - 0.0000000002224\ \text{Area}^3. \quad (10)$$

This equation needs to be validated by testing it on the same dataset used in the analysis. The comparison is made on the calculated $f_{\rm dirt}$ obtained from (9) and the calculated $f_{\rm dirt}$ in (10). The difference is shown in Fig. 9.

Fig. 9 shows that both curves have similar pattern. The range of the difference as a percentage of $f_{\rm dirt}$ obtained from (9) and the latest calculated $f_{\rm dirt}$ by using (10) is from 1.68% to 8.79% with an average of 5%. Mean average percentage error, (MAPE) for (10) is found to be 5%, whereas root-mean-squared error (RMSE) is 1.01, which shows that the equation is quite acceptable [32].

This scenario indicates that, in this research site, soiling can be dispersed widely with the increment of the PV module area as it is usually carried by the wind. With a small PV module area, the effect of soiling can be severe. However, according to the data from this site and the prediction of the cubic function equation model, the mitigation of soiling by having more PV modules or more installed PV capacity is found unreliable. Soiling can occur anywhere within the PV modules' surface.

Even though the calculated results from (10) is not practically 100% accurate, it is still able to produce values near to the real data within the inaccuracy less than 10%. Hence, it still can be used to forecast $f_{\rm dirt}$ in this site. In addition, the forecasting can be much simpler by using this equation compared to the $f_{\rm dirt}$ forecasting by using the empirical (4), which requires many parameters and constants (PSF, $f_{\rm temp}$, $P_{\rm AC}$, $\gamma_{\rm pmp}$, etc.) Meanwhile, the developed model (10) is able to predict $f_{\rm dirt}$ of PV module area in this site by using the only known area of the module. On the other hand, soiling estimation through the relationship of $f_{\rm dirt}$ and PV module area or size is still absent from the published research literature as discussed in Section III.

VI. Conclusion

From this research, the impact of soiling on PV system's performance in a fully humid tropical country has been identified at the research site. Subsequently, the study has led to the development of a new mathematical model, much simpler and less inaccurate to predict $f_{\rm dirt}$ with only known area of the PV module. Following are the conclusions to be made from this research.

1) The observation of the PV system has allowed $f_{\rm dirt}$ for the research site to be determined. The finding indicates that $f_{\rm dirt}$ for the studied site in Malaysia, a highly humid tropical country, is at an average of 26.22% during the observation year. The readings ranged from as low as 4.86% to as high as 58.67% and this value can vary accordingly from time to time depending on the site characteristics.
2) The analysis of $f_{\rm dirt}$–module area is found to be significant, and from this, a new mathematical model has been regressed and developed. The new model deviates from the previous used model (9) from 1.68% to 8.79% with an average of 5% when comparing the accuracy of forecasts using the same data. The calculated MAPE for this model is found at 5%, whereas RMSE at 1.01 shows that the equation is acceptable and applicable for the researched site. By using this mathematical model in the same research site, the $f_{\rm dirt}$ forecasting can become much simpler with just one variable: the module's area or size. This will simplify the soiling prediction performed for that site. Besides, the same correlation and regression method can be performed for other sites to produce the new $f_{\rm dirt}$ prediction model. Actually, this forecasting is important to provide the information for the planning of

new PV system prior to soiling effect and schedule for soiling mitigation.

ACKNOWLEDGMENT

The authors were grateful to the plant owner of the studied PV system which is located in Setiu, Malaysia (Latitude = 5.5167° North; Longitude = 102.7667° East), Synergy Generated Sdn. Bhd (Company registration no: 918256-K) for the permission to access and use the plant data for this study.

REFERENCES

[1] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renewable Sustain. Energy Rev.*, vol. 14, pp. 3124–3131, 2010.

[2] M. M. Fouad, L. A. Shihata, and E. I. Morgan, "An integrated review of factors influencing the perfomance of photovoltaic panels," *Renewable Sustain. Energy Rev.*, vol. 80, pp. 1499–1511, 2017.

[3] T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches," *Renewable Sustain. Energy Rev.*, vol. 22, pp. 698–733, 2013.

[4] S. Mekhilef, R. Saidur, and M. Kamalisarvestani, "Effect of dust, humidity and air velocity on efficiency of photovoltaic cells," *Renewable Sustain. Energy Rev.*, vol. 16, pp. 2920–2925, 2012.

[5] B. Figgis, A. Ennaoui, S. Ahzi, and Y. Rémond, "Review of PV soiling particle mechanics in desert environments," *Renewable Sustain. Energy Rev.*, vol. 76, pp. 872–881, 2017.

[6] A. Sayyah, M. N. Horenstein, and M. K. Mazumder, "Energy yield loss caused by dust deposition on photovoltaic panels," *Solar. Energy.*, vol. 107, pp. 576–604, 2014.

[7] R. Conceição *et al.*, "Saharan dust transport to Europe and its impact on photovoltaic performance: A case study of soiling in Portugal," *Solar. Energy.*, vol. 160, pp. 94–102, 2018.

[8] B. Weber, A. Quiñones, R. Almanza, and M. D. Duran, "Performance reduction of PV systems by dust deposition," *Energy Procedia*, vol. 57, pp. 99–108, 2014.

[9] F. Rubel and M. Kottek, "Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification," *Meteorologische Zeitschrift*, vol. 19, no. 2, pp. 135–141, 2010.

[10] S. A. Kalogirou, R. Agathokleous, and G. Panayiotou, "On-site PV characterization and the effect of soiling on their performance," *Energy*, vol. 51, pp. 439–446, 2013.

[11] M. Gostein, T. Düster, and C. Thuman, "Accurately measuring PV soiling losses with soiling station employing module power measurements," in *Proc. IEEE 42nd Photovolt. Specialist Conf.*, 2015, pp. 1–4.

[12] R. Cordero *et al.*, "Effects of soiling on photovoltaic (PV) modules in the Atacama Desert," *Scientific Rep.*, vol. 8, pp. 1–14, 2018.

[13] L. Micheli, D. Ruth, and M. Muller, "Seasonal trends of soiling on photovoltaic systems," in *Proc. IEEE 44th Photovolt. Specialist Conf.*, 2017, pp. 2301–2306.

[14] M. T. Muller, D. Ruth, and L. Micheli, "Seasonal trends of soiling on photovoltaic systems," in *Proc. IEEE Photovolt. Specialist Conf.*, 2017, pp. 2301–2306.

[15] M. T. Latif *et al.*, "Impact of regional haze towards air quality in Malaysia: A review," *Atmospheric Environ.*, vol. 177, pp. 28–44, 2018.

[16] R. D'Arrigo, J. Palmer, C. C. Ummenhofer, N. N. Kyaw, and P. Krusic, "Three centuries of Myanmar monsoon climate variability inferred from teak tree rings," *Geophys. Res. Lett.*, vol. 38, 2011.

[17] S. C. Costa, A. S. A. Diniz, and L. L. Kazmerski, "Dust and soiling issues and impacts relating to solar energy systems: Literature review update for 2012–2015," *Renewable Sustain. Energy Rev.*, vol. 63, pp. 33–61, 2016.

[18] S. A. Sulaiman, A. K. Singh, M. M. M. Mokhtar, and M. A. Bou-Rabee, "Influence of dirt accumulation on performance of PV panels," *Energy Procedia*, vol. 50, pp. 50–56, 2014.

[19] T. Khatib, A. Mohamed, K. Sopian, and M. Mahmoud, "A new approach for optimal sizing of standalone photovoltaic systems," *Int. J. Photoenergy*, vol. 2012, 2012.

[20] A. Kimber, L. Mitchell, S. Nogradi, and H. Wenger, "The effect of soiling on large grid-connected photovoltaic systems in California and the southwest region of the United States," in *Proc. Conf. Rec. IEEE 4th World Conf. Photovolt. Energy Convers.*, 2006, pp. 2391–2395.

[21] E. Kymakis, S. Kalykakis, and T. M. Papazoglou, "Performance analysis of a grid connected photovoltaic park on the Island of Crete," *Energy Convers. Manage.*, vol. 50, pp. 433–438, 2009.

[22] D. Thevenard and S. Pelland, "Estimating the uncertainty in long-term photovoltaic yield predictions," *Solar. Energy.*, vol. 91, pp. 432–445, 2013.

[23] L. Cristaldi *et al.*, "Economical evaluation of PV system losses due to the dust and pollution," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, 2012, pp. 614–618.

[24] M. Gostein, J. R. Caron, and B. Littmann, "Measuring soiling losses at utility-scale PV power plants," in *Proc. IEEE 40th Photovolt. Specialist Conf.*, 2014, pp. 885–890.

[25] A. M. Pavan, A. Mellit, and D. De Pieri, "The effect of soiling on energy production for large-scale photovoltaic plants," *Solar. Energy.*, vol. 85, pp. 1128–1136, 2011.

[26] J. Lopez-Garcia, A. Pozza, and T. Sample, "Long-term soiling of silicon PV modules in a moderate subtropical climate," *Solar. Energy.*, vol. 130, pp. 174–183, 2016.

[27] A. M. Omar, S. Shaari, and S. I. Sulaiman, "Grid-connected power systems design," Sustainable Energy Development Authority (SEDA), Putrajaya, Malaysia, vol. 1, 2012.

[28] M. G. Deceglie, M. Muller, Z. Defreitas, and S. Kurtz, "A scalable method for extracting soiling rates from PV production data," in *Proc. IEEE 43rd Photovolt. Specialists Conf.*, 2016, pp. 2061–2065.

[29] J. Benesty, J. Chen, Y. Huang, and I. Cohen, "Pearson correlation coefficient," in *Noise Reduction in Speech Processing*. Berlin, Germany: Springer, 2009, pp. 1–4.

[30] P. Sedgwick, "Pearson's correlation coefficient," *BMJ*, vol. 345, 2012.

[31] J. Cohen, P. Cohen, S. G. West, and L. S. Aiken, *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences*. Evanston, IL, USA: Routledge, 2013.

[32] J. S. Armstrong and T. S. Overton, "Estimating nonresponse bias in mail surveys," *J. Marketing Res.*, vol. 14, pp. 396–402, 1977.

Wan Juzaili Jamil received the master's degrees in occupational safety and health management and in electrical engineering from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 2013 and 2018, respectively.

He is currently a Graduated Research Officer and a Ph.D. Student undertaking research on PV-thermal system with the School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal, Malaysia.

Hasimah Abdul Rahman (Member, IEEE) received the B.Sc. degree in electrical and electronic engineering from the University of Aberdeen, U.K., in 1988, the M.Sc. degree in energy studies from the University of Wales, College of Cardiff, in 1995, and the Ph.D. degree in electrical engineering from Universiti Teknologi Malaysia, in 2012.

She was an Associate Professor with the Faculty of Electrical Engineering and also the Deputy Director of the Centre of Electrical Energy Systems (CEES), Universiti Teknologi Malaysia, Johor Bahru, Malaysia, until 2018. She has more than 20 years of experience in teaching electrical engineering courses and supervising more than 60 undergraduates and 10 post graduates students. She has authored and coauthored for more than 41 journal and conference papers. Her specialized area of research is on solar photovoltaic.

Sulaiman Shaari received the B.Sc. and M.Sc. degrees in physics, each from Kansas State University, Manhattan in 1984 and from University of Missouri, Kansas City, in 1987, both from United States of America. Later in 1998, he completed his Ph.D. in photovoltaic systems from De Montfort University, Leicester, United Kingdom.

He is currently a Professor with the Universiti Teknologi MARA, Shah Alam, Malaysia. Besides doing the regular academic job such as teaching, supervising, and researching, he is a member of the Green Energy Research Centre, and the founding Director of the Photovoltaic Systems Monitoring Centre (PVMC). The PVMC has been a center of reference from many agencies, and local and international companies.

Mohd Khairunaz Mat Desa (Member, IEEE) received the master's degree in electrical engineering from Loughborough University, United Kingdom, in 2008 and Ph.D. degree in renewable energy from National University of Malaysia, Bangi, Selangor, in 2014.

He is a Senior Lecturer with the School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Nibong Tebal, Malaysia. He is specialized in solar photovoltaics (silicon technology applications), photovoltaic-thermal, renewable energy (wind, biomass, hydropower, etc.), power electronics, and energy policy.