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A New Correlation for Solar Radiation Incidence Angle and Dust Accumulation of Photovoltaic PV Systems

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It can be considered that electric generating power from solar energy is an essential topic in the energy field. Several environmental factors affect the energy production of solar cells. Dust accumulation is one of the main factors which significantly negatively influences output energy. However, this topic is not investigated extensively, despite its significant impact, especially in arid areas such as Iraq. In this research paper, both theoretical and experimental techniques were applied to investigate the effect of accumulated dust particles on the efficiency of photovoltaic PV systems. An on-grid photovoltaic system was selected to achieve the experimental work. The results proved the negative effect of dust particles on the performance of the solar cell. Based on the obtained results, a new relationship was introduced between efficiency degradation and the amount of dust that accumulated on the surfaces of cells. This correlation is considered a necessity to find the characteristics of PV solar systems to improve their performance and efficiency. The new correlation introduced in this paper can be considered a promising prediction tool to estimate the characteristics of photovoltaic solar cells under different actual environment working conditions. The output power of the cleaned array system increased by 5–26% compared with the untreated system over the test period. Furthermore, the performance ratio (PR) was enhanced within the cleaned array system by 3 to 6 compared with the uncleaned array. A significant formula introduced the connection between the actual output power of the PV systems and the environmental condition (dust accumulation), where it can be considered as feedback to keep the performance in a steady status, which means obtaining the highest output power.

Keywords: photovoltaic efficiency, radiation attenuation, dust accumulation, output power.

Introduction

Solar energy is considered the primary renewable clean energy source that is free to use to produce electricity (Zorrilla-Casanova, 2011). However, researchers face many challenges, such as low efficiency, weather effects such as high temperatures, energy storage, etc. (Gong and Wasielewski, 2019). One of the important solar energy applications is the PV solar systems that are connected to the national grid (Styszko et al., 2019; Kashan and Al-Qrimli, 2020). These PV systems face the dust accumulation problem that minimizes the solar radiation absorbed by the PV solar panels. As a result of this problem, the output power generated will decrease dramatically (Obaid et al., 2019; Obaid et al., 2020). The dust effect on solar radiation transition varies according to the solar radiation incidence angle (Al-Hasan, 1998).

Several studies have been conducted on dust accumulation effects on PV solar modules. The effect of the accumulations of dust on glass plates of various tilted angles was investigated by Hegazy (2001). Also, the solar transmittance reductions were studied experimentally during one year in the “Minia region, middle of Egypt” climate conditions. The obtained results clarify a partial reduction in radiation transmittance. They found that the output depends substantially on the accumulation of dust conjunctive with plate tilted angle, site climate conditions, and time.

Kazem et al. (2020) analyzed experimentally the impact of dust accumulation on the output power of PV modules. The dust was obtained from three specified locations in “The Sultanate of Oman”. The results showed that 64% of the total dust particles were 2–63 μm in diameter. The dust deposition effect on PV modules was investigated for different locations.

The concentration of the surface mass of the deposited dust on the photovoltaic unit is limited to less than 1 g/m^2; within this condition, the reduction in output energy was limited. The maximum daily decrease in efficiency was 0.05% for the examined samples, which was considered a small value. The results showed that the exposure of the photovoltaic cells to outdoor conditions longer than three months caused a decrease in the PV module yield by 35–40%.

Another study in Poland investigated the maximum deposited dust on PV solar systems. The dust density deposited weekly was 300 mg/m^2 in case of rainless weather, and consequently, the efficiency loss was found to be 2.1%. They found that the losses typically depend on accumulated dust properties (Jaszczur et al., 2019).

Kawamoto and Takuya (2018) developed a mathematical model for PV module's efficiency degradation taking into consideration dust accumulation. Moreover, the efficiency of cleaning six types of sand from various deserts was investigated using the electrostatic cleaning system. The experimental work showed that more than 90% of the adhering dust is repelled from the surface of the slightly inclined panel after the cleaning operation. Consequently, the system performance was further improved by electrode configuration enhancement as well as the influences of natural wind on the panel surface.

Based on many studies, it can be considered that Iraq is one of the most popular countries that suffers from dusty weather. Almost all studies recommend achieving schedule cleaning for PV systems to avoid the negative dust effects on PV modules (Kawamoto and Shibata, 2015; Al-Nimr and Al-Shohani, 2013).

In this work, the dust layer effect on the transmittance of beam radiation on the PV module's glazing surface was investigated mathematically and approved experimentally for a 15 kW PV solar system. This correlation can be considered a promising tool that guides the designers of PV systems to estimate the actual output power obtained under different climatic conditions (dust accumulation and angle incident of solar radiation).

This work is considered a promising tool that can be used to study and analyze the characteristics of PV solar systems in dusty sites. Then, the minimum period necessary for cleaning the PV systems to maintain the optimal efficiency to obtain the highest power can be determined. The developed approach in this research paper can be used to predict the PV solar system's output power (efficiency) under different environmental conditions (accumulated dust particles). This will be very useful, and based on the results, automated cleaning units can be used to clean PV solar systems within a specific period.

Experimental Work

The 15 kW on-grid PV solar system located at the Training and Energy Research Office subsidiary of the Iraqi Ministry of Electricity Bagdad, Iraq, was selected to conduct the experimental work. However, the location of the selected system geographically is at 44.4 °E longitude, 33.3 °N latitude, and elevation of 41 m above sea level. The PV system tilted angle was 30°, and it was south facing, i.e., had a zero azimuth angle, as shown in *Fig. 1*. The current PV system was connected to the feeder with continuous electricity provided to the main building via smart meters.

Fig. 1. *The 15 kW PV solar system*

The PV system included 72 PV modules "Model: HIT-205DNKHE1" with an area covering 83.57 m^2. The PV module provides 205 Wp (more details in (SANYO, 2021; Ogbulezie et al., 2020). An inverter used in the current system was "SMA Sunny Tripower, 15000 TL-10 type" (SMA, 2020). This inverter has a maximum rated efficiency of 97% for a 15 kW capacity. It is combined with a monitoring system linked to the Sunny portal program that can provide daily, monthly and yearly data for power production.

However, two cases/strings (cleaned/uncleaned) were selected, as shown in *Fig. 2*, and each case consists of 12 modules. During the experiment, a comparison was made between both cases to evaluate the influence of dust on the solar system's performance. The uncleaned string represented the reference string. The range of the size of dust particles recorded in Baghdad city is 2–62 μm for silica and 0.5–2 μm for clay particulates (Kadhum and Rasheed, 2018; Kasim et al., 2021; Katee et al., 2021).

The cleaned case was cleaned periodically using a pressurized water system, as shown in *Fig. 3*. Both strings were tested simultaneously under the same

Fig. 2. *The cleaned and uncleaned arrays*

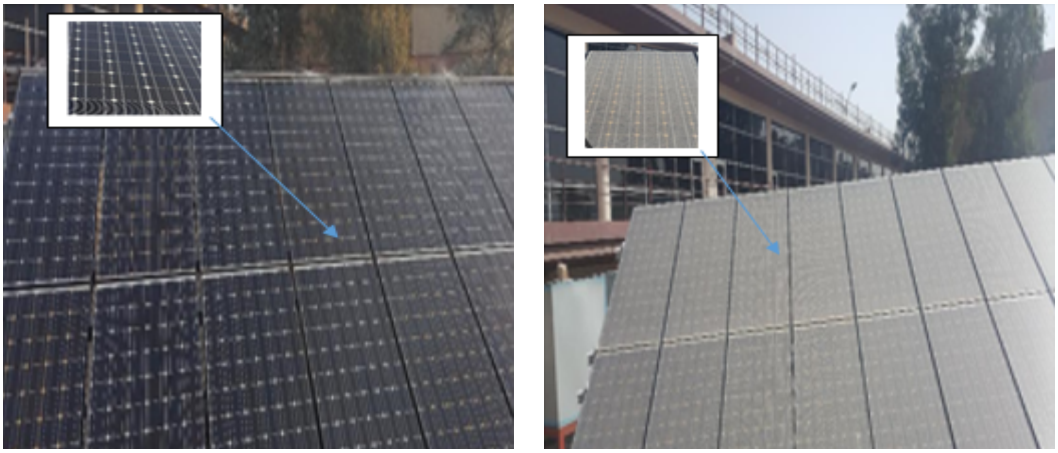


Fig. 3. *The structure of the solar panel cleaning system*

conditions of solar radiation and ambient temperatures. The instantaneous power output was collected for each string using the SUNNY EXPLORER program. The cleaning system was controlled by a relay connected to the pump and programmed to work for 30 minutes to open the pump and clean up the PV system, as shown in *Fig. 4*.

Fig. 4. *The cleaning system pump connected to the relay*

Fig. 5 represents the 15 kW on-grid solar inverter (SMA- SUNNY TRI POWER 15000 TL), where the connection between the computer and the inverter can be seen. So, the instantaneous rate time data of the PV system for each AC and DC side current-voltage and current-power for the solar system can be obtained. This instantaneous data were given by SUNNY EXPLORER software that monitors the PV system via Bluetooth with a quick overview of yields and plant status. A solar power meter (TES 1333R Data logging) was used to measure solar radiation, where the accuracy of this device is ±10 w/m^2 or ±5%.

Theoretical Formulation

When the light hits a small dust particle, it is reflected or absorbs some of the light that decreases the light intensity, which is called the extinction process (Al-Hasan, 2005). The scattering of light is governed by the ratio of particle size and wavelength of the incident light, which is called the size parameter and calculated as follows:

Fig. 5. *Grid-tied solar inverter (SMA-SUNNY TRI POWER 15000 TL)*

$$\alpha = \frac{\pi D}{\lambda} \tag{1}$$

Where: D is the particle diameter; λ is the wave length of solar radiation.

Extinction of light is a function of particle extinction efficiency Qe. The particle is small compared with the wavelength, $\alpha < 0.3$. The particle extinction efficiency that follows Rayleigh scattering is as follows:

$$Qe = \frac{8\alpha^4}{3}\left[\frac{m^2-1}{m+2}\right]^2 \tag{2}$$

Where: m is the particle refractive index.

The particle extinction efficiency in this case is much less than unity, and the scattering is very sensitive to the wavelength of solar radiation. The scattering decreases rapidly with increasing wavelength. For a larger particle size, when $\alpha > 0.3$, i.e., the particle diameter is larger than 0.05 μm, the particle extinction efficiency (Qe) will follow Mie scattering, which is a more complex problem. In this case, the particles are larger with a diameter greater than 2 μm, $\alpha > 12$ and Qe approaches with oscillations to the value of 2. In this case, it is considered that the light will be scattered by reflection, refraction partially, and some amount will be absorbed. When the particle is very large compared with the light wavelength, the particles will not be influenced by the light wavelength, Qe will be constant, and the particles will remove the light equal to its projective area.

In photovoltaics, the effect of N particles of dust steady beside each other on the PV module surface will cover the area of $N\pi r^2$. The dust particle geometry is assumed to be a spherical shape of diameter D, radius r and density ρ. Assuming that, the dust particles of the full layer are to be formed before the formation of the second layer. When the particles are fixed beside each other until they cover an area of 1 cm^2, they are distributed as shown in *Fig. 6*. The following formula can be applied when the incident angle is zero:

$$A_c = \frac{1.5M}{\rho D}\,\text{cm}^2 \tag{3}$$

Fig. 6. *The arrangement of spheres when covering 1 cm^2 area (Al-Hasan, 2005)*

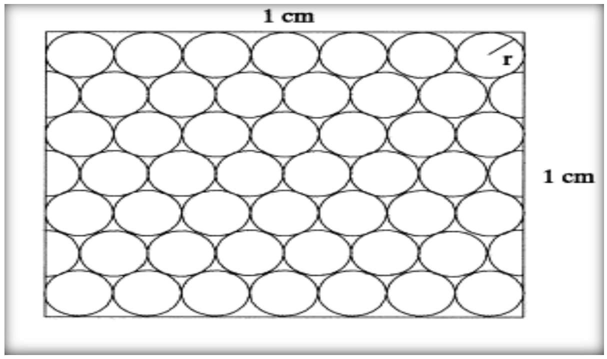
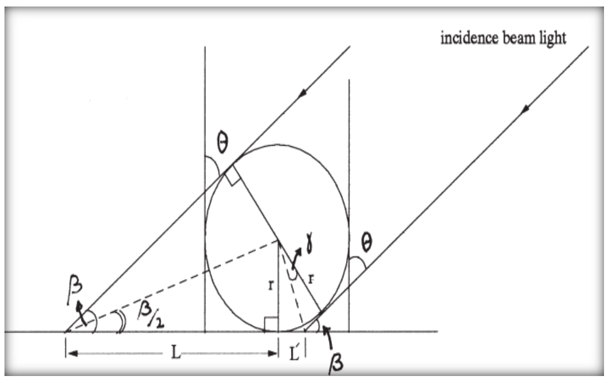


Fig. 7 shows the area covered by the particles while the beam light reaches the glass surface with an incidence angle θ. The area covered in this case is ellipsoid geometry (Al-Hasan, 2005), so it can be found as follows,

$$Ac(\theta) = N\pi r\left(\frac{L+L'}{2}\right) = \frac{3M}{4\pi\rho r3} \times \frac{\pi r2}{2} \times \left[\frac{1}{\tan\left(\frac{90-\theta}{2}\right)} + tan\left(\frac{90-\theta}{2}\right)\right] \tag{4}$$

Fig. 7. *Area covered by a particle while the beam light reaches the glass surface with an incidence angle θ (Al-Hasan, 2005)*



The beam radiation component due to dust particles can be written as follows:

$$I_{b(s)} = I_b\,\tau_{b(\theta)} \tag{5}$$

Meanwhile, the transmittance $\tau_{b(\theta)}$ at different incidence angle is:

$$\tau_{b(\theta)} = 1 - QeA_{c(\theta)} \tag{6}$$

The light transmittance at a 90° incidence angle should equal zero due to the infinity-covered area. This transmittance may reach zero before 90° incidence angles at higher dust accumulated on the glass surface, where the area between particles will be shaded at an angle less than 90°. The total solar radiation that is incident on PV solar modules is as follows (Duffie and Beckman, 2013):

$$I_t = I_{DN}\left[COS\Theta + C\frac{(1+COS\beta)}{2} + \rho\frac{(C+Sin\alpha)(1-COS\beta)}{2}\right] \quad (7)$$

Where: I_{DN} – direct normal solar radiation; Θ – solar radiation incident angle; C – diffuse factor.

Substituting Eq. (5) into Eq. (7) gives the following:

$$I_t = \frac{Ib\tau b(\theta)}{COS\theta}\left[\cos\theta + C\frac{(1+cos\beta)}{2} + (\rho\frac{(C+sin\alpha)(1-COS\beta)}{2}\right] \quad (8)$$

where the efficiency is:

$$\eta_{PV} = \frac{PDC}{It}\ \% \quad (9)$$

Substituting Eq. (9) into Eq. (8) gives the DC power output of the PV solar system as follows:

$$P_{DC} = \eta_{PV} \times A_m \times \frac{Ib\tau b(\theta)}{COS\theta}\left[\cos\theta + C\frac{(1+cos\beta)}{2} + (\rho\frac{(C+sin\alpha)(1-COS\beta)}{2}\right] \quad (10)$$

Where: η_{PV} is the PV module efficiency; A_m is the array area (m^2).

The Data and Environment Conditions

In this work, N dust particles were assumed stabilized beside each other on the module surface, with the particles as a spherical shape with mean diameter D (cm) and mean radius r (cm). The mathematical model is based on the assumptions of an equal size of spherical particles and uniform distribution; the complete layer of sand dust particles is formed before the beginning of the second layer formation. The deviation between the measured results and the mathematical results was presented. Then dust particles are fixed beside each other until they cover the whole area of 13.92 m^2 (string area). Eq. (4) is applied when the incident angle is larger than zero.

The environmental conditions of the achieved tests are as follows:

1 Measured beam solar radiation (W/m^2): 413.3, 447.56, 485.48, 566.74, 596.85, 627.63, 666.87, 679.41, 696.47, 694.54, 703.38, 638.34, 674.23, 668.77, 609.56, 591.15, 539.93, 517.27, 497.09, 455.75, 422.86 during the period of tests;
2 Dust particle diameter: 6 μm (Al-Hasan, 2005);
3 Particles number: $4.1760 \cdot 10^9$ (Al-Hasan, 2005);
4 Time of the test: between 9:15 AM and 3 PM;
5 Date of the test: 21/1/2021.

Numerical Analyses of the Dust Effect

Numerical analyses were used to understand the relation between the solar radiation incident angle, dust accumulation on PV solar systems, and their influence on power production. Namely, the variation of the solar incident angle has an effect on the dust covering the area. A new relation was introduced to assist the PV system designers in predicting the power generation and beam solar radiation that can reach the surface of the module. Reached solar radiation was related as a function of the particle's dust size and the amount of accumulated dust on the surface.

Results and Discussions

A MATLAB model was established to estimate the power production of the system that is influenced by the incident angle and dust particle accumulation. This can cause scattering and absorption of incident solar radiation and consequently decrease solar radiation intensity. The incident solar radiation angle was calculated. The results show that the gradual decreases in solar incident angle until reaching 53° at 12:15 PM mean a high magnitude of solar radiation and a maximum output power, as shown in *Fig. 8*.

The results presented the difference in energy between cleaned and uncleaned strings, where the maximum energy gains occurred between 9:15 AM to 10:45 AM. This can be attributed to the area exposed to solar radiation being much less than the cleaned string (the area depends on solar incident angle value).

The power gain was stabilized and decreased in the previous period time (between 11 AM and 1:30 PM), due to the reduction in the area exposed to the solar radiation for cleaned and uncleaned strings (reference). The incident angle's magnitude significantly influences the exposed area's solar radiation. Moreover, the power gain curve began to increase over a period of time between 1:45 PM and 3 PM. In this case, the incidence angle value became larger than that in the mourning period time, which led to changing the exposed area to light to become larger, as shown in *Fig. 9*.

Fig. 8. *Simulated incident angle variation over a period of time*

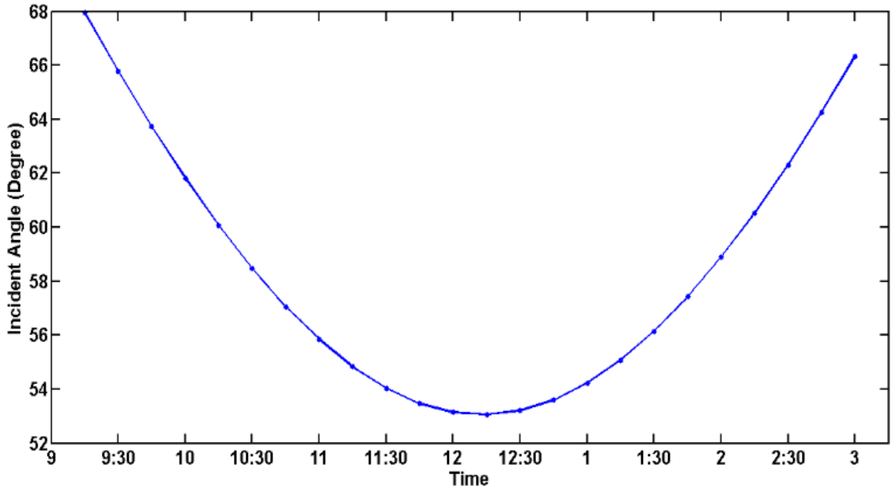
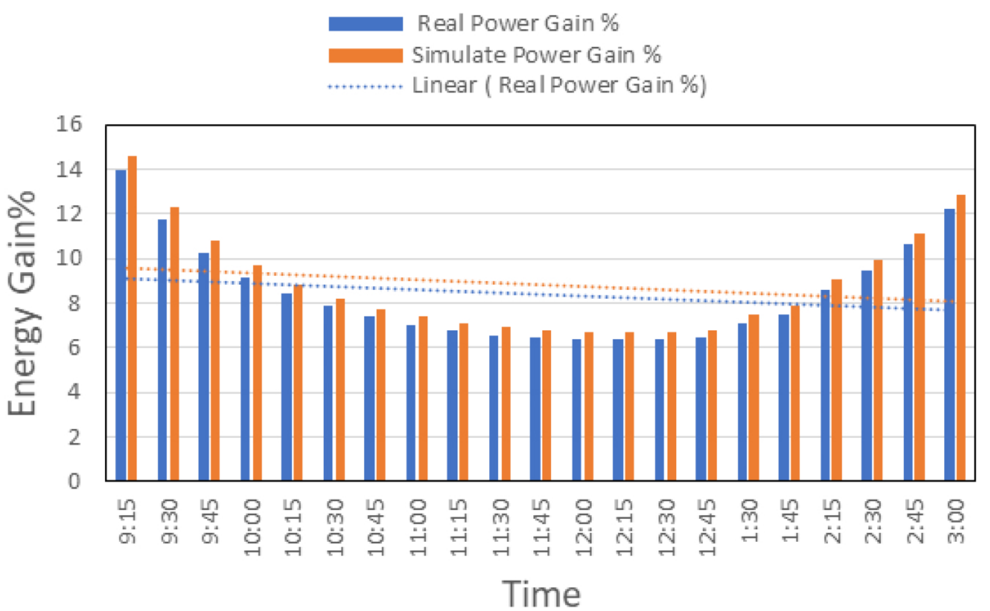


Fig. 9. *Measured and simulated power gain percentage of the PV solar system*



The average simulated power gain of strings was 8.8% which illustrated the behavior of the measured power gain percentage of 8.4% during the daytime (January 21st). At the same time, the percentage error was found to be 4.7%, which occurred due to an error in measured solar radiation values.

Accordingly, the experimental work was conducted one day per week to study the effect of removing dust from the surface of a 15 kW PV solar system and then compare the results of cleaned and uncleaned arrays based on the performance parameters. However, a reasonable amount of pumping water was selected to clean the area of 14 m^2 with a standard period of 0.5 min. An automatic control system was used for the cleaning sprayer system, which led to higher energy during the period of the experiment. However, the low energy is needed ($9.8 \cdot 10^{-3}$ kWh) for the cleaning system motor (1180 W water pump) where this power was taken into account to find the net output of the solar system.

Fig. 10 illustrates the average solar insolation in the selected month (5.322 kWh/m^2), while the average output power for the cleaned array was 9.498 kWh. However, it was observed that high energy (0.98 kWh) was obtained on January 14th. At the same time, the lower value (0.33 kWh) occurred on January 7th due to the unstable weather between rainy and dusty days. On this day, the whole system was exposed to rain, which reduced the energy of the two arrays. On the next test day (January 14th), the system was accompanied by a light wave of dust that led to a clear energy difference, hence the percentage of gain energy obtained due to the cleaning up was 4.3–12.19% higher than the uncleaned array in January.

It was noticed that the array losses were decreased due to a cleaning process, and the losses caused by the accumulation of dust were reduced to the minimum value of 0.13 kWh/kWP on January 7th, and the maximum difference of 0.38 kWh/kWP occurred at the same date. On January 21st, as shown in *Fig. 11*, a different range of enhancement can be seen in the output power (5–26%) when the cleaning process was achieved, which can be attributed to the wide range of weather fluctuations in winter from rain and light dust waves.

Fig. 12 demonstrates the efficiencies of the cleaned and uncleaned (dirty) arrays of the 15 kW PV solar system. The values of efficiencies for the cleaned and uncleaned arrays varied within 12.3–14%, 10.18–12%, 13–14.35% and 9.38–10.2% on the dates of January 30th, 21st, 14th, and 7th, respectively. Meanwhile, the minimum efficiency $\Delta\eta$ (0.82) acquired increased during the rainy period on January 7th. The maximum efficiency $\Delta\eta$ was 1.82 with reference efficiency, which increased on January 21st, occurring on a dry day (light dust wave).

Fig. 10. *Solar radiation and strings energy output*

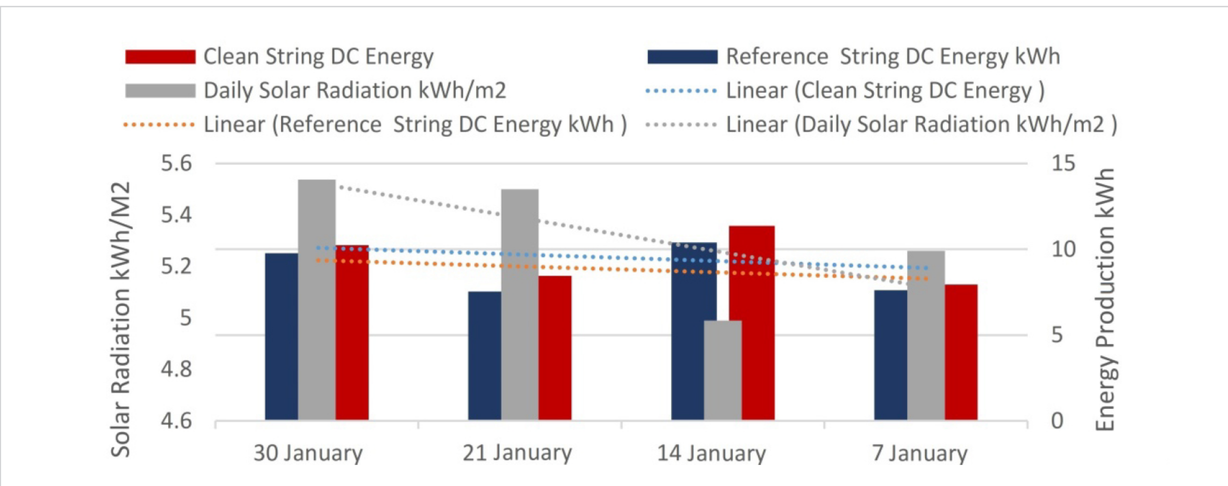


Fig. 11. *Cleaned and uncleaned arrays and system losses of the 15 kW PV solar system*

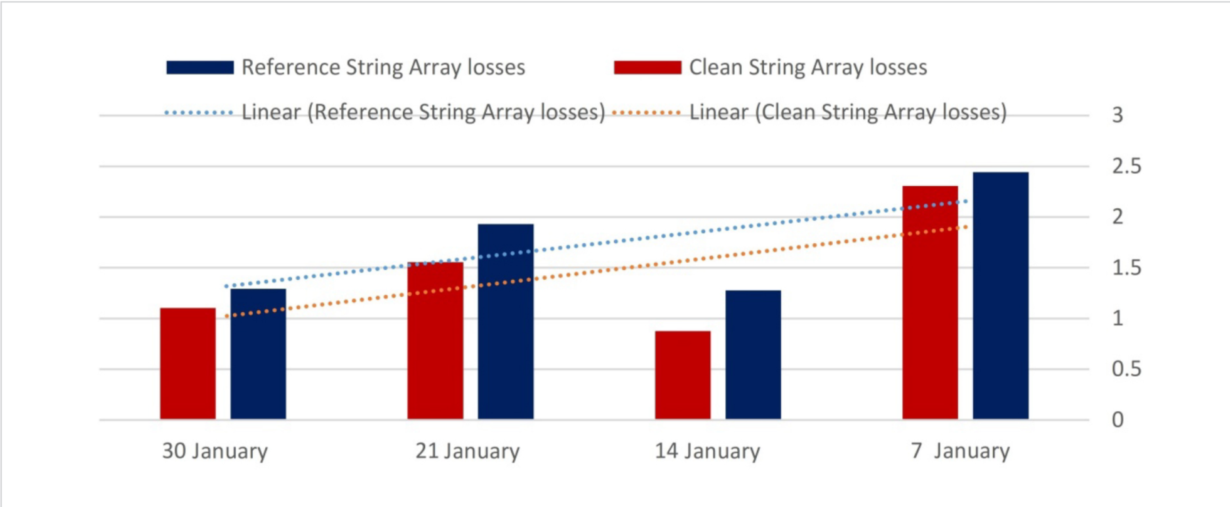
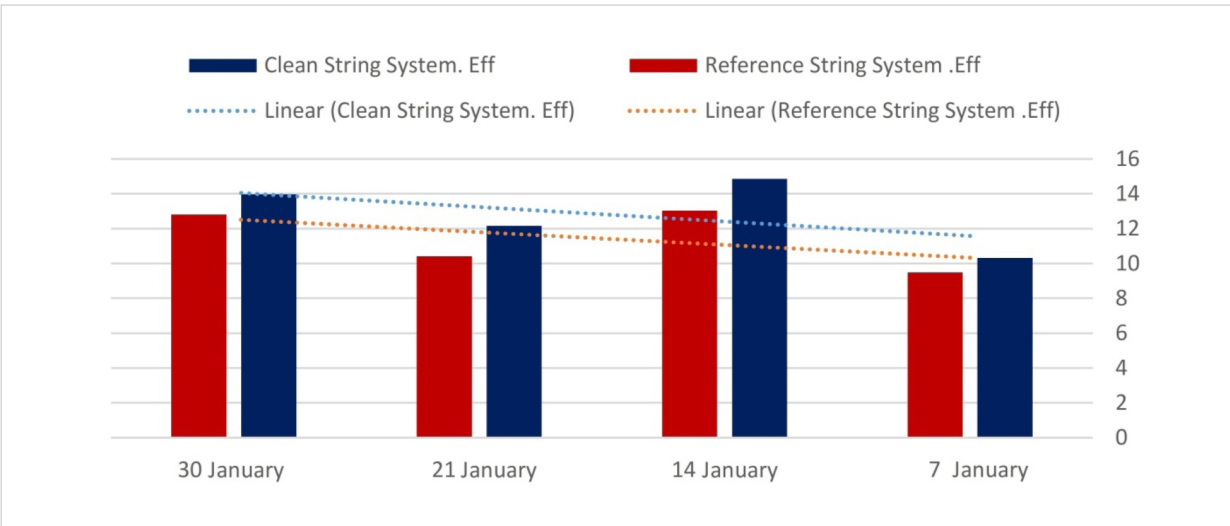


Fig. 12. *The efficiencies of cleaned and uncleaned arrays of the 15 kW PV solar system*



Besides, the final energy yields refer to the number of days the PV solar system can generate alternating energy with its nominated capacity (Obaid et al., 2021; Kasim et al., 2020). *Fig. 13* demonstrates the cleaned and uncleaned yields of the 15 kW PV solar system. Finally, the minimum final energy yield difference (uncleaned) was found to be 0.13 on January 7th, while the maximum value was found to be 0.4 on January 21st for the cleaned array.

Moreover, the physical meaning of performance ratio (PR) represents the ratio of the PV solar system's real to perfect energy output (Yadav and Bajpai, 2018; You et al., 2013).

Fig. 14 shows that the PR and the minimum PR difference were found to be 3 on January 7th, while the maximum value was found to be 6 on January 2nd and this reflects positively on the real energy production.

Fig. 13. *The yields of cleaned and uncleaned arrays of the 15 kW PV solar system*

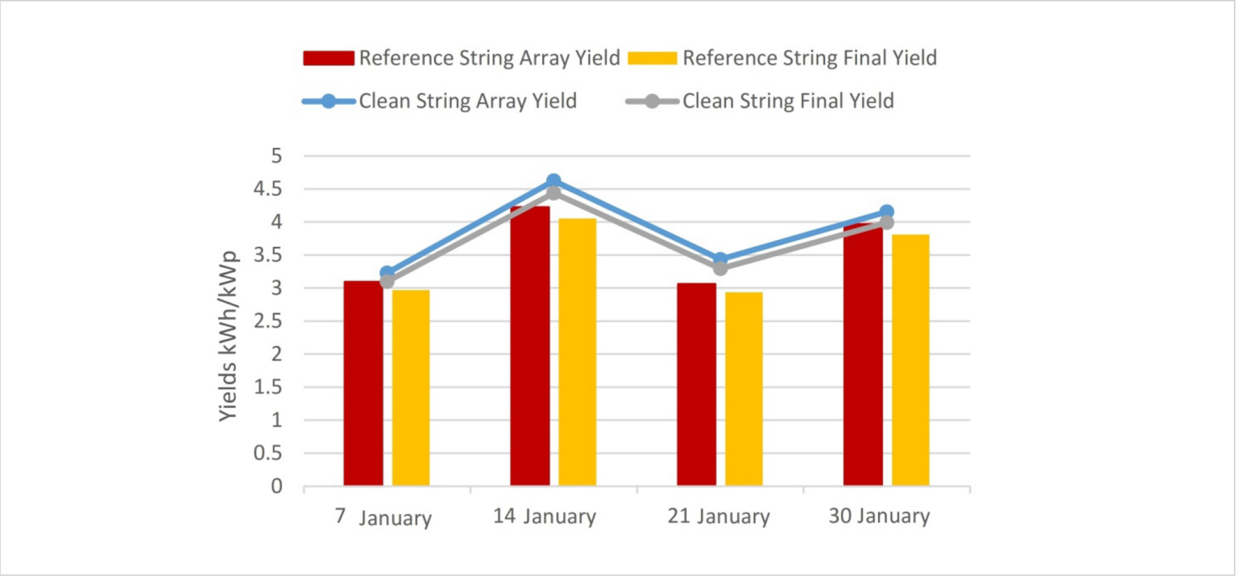
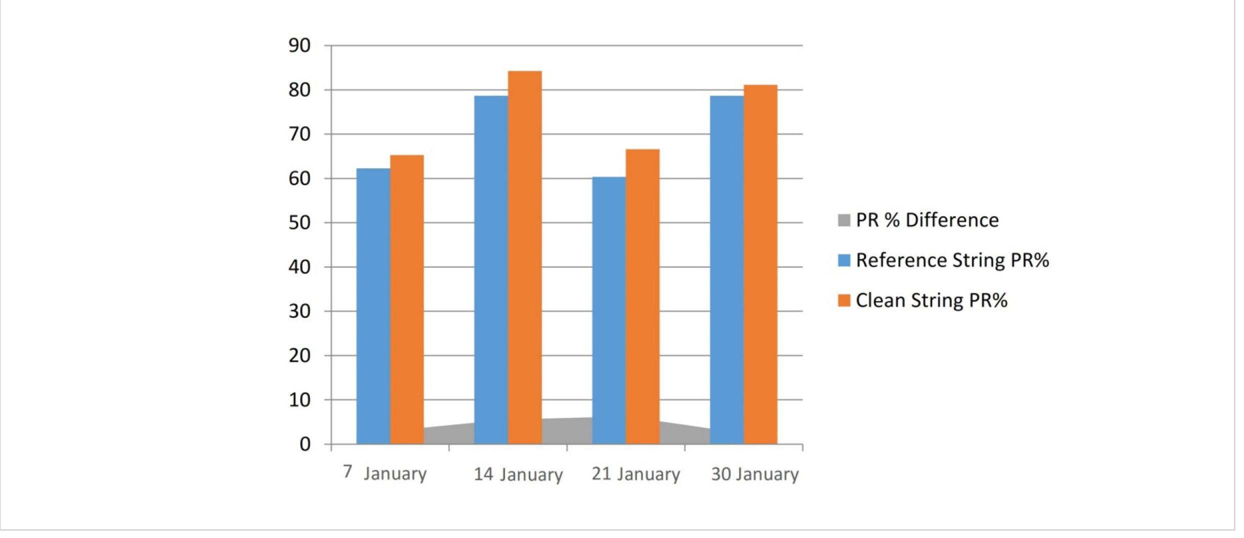


Fig. 14. *The performance ratio (PR) of cleaned and uncleaned arrays of the 15 kW PV solar system*



Conclusions

Dust accumulation greatly affects the performance of photovoltaic modules. This problem is significant in dusty areas, especially desert locations. In this research paper, a theoretical investigation was achieved using the developed mathematical model to find the compound effects of the solar radiation incidence angle and dust accumulation on the output power of the system. In order to achieve the calculations and analyses of this work, a new code using MATLAB software was built. A high agreement was achieved between the results of the simulation and experiment, where the difference between them did not exceed 5% during the day period.

The energy gain was high during the sunrise and sunset period; as a result of this fact, the longest period of time to calculate the gain of energy should be considered. Furthermore, the percentage of losses was reduced when using the cleaned array system by 5–26% compared with the uncleaned one during the test period. This process has a significant effect on enhancing the performance and efficiency of the solar system. The results proved that the cleaning system in locations such as Iraq (most cities have the same problem, but the level is different from one city to another) is necessary to get the highest power from the PV solar systems. The range of the equivalent enhancement of the power output is between 11% and 24% compared with the uncleaned array, while the enhancement of PR was found between 3 and 6 compared with the uncleaned array.

Acknowledgments

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Nomenclatures

Symbol	Description
PR	Performance ratio
λ	Wavelength of solar radiation
D	Particle diameter
α	Size parameter
Qe	Particle extinction efficiency
m	Particle refractive index
ρ.	Density of the particle
r	Radius of the particle
θ	Incidence angle
Ac	Covered area
I_b	Beam radiation component
τ_b	Transmittance
I_{DN}	Direct normal solar radiation
C	Diffuse factor
η_{PV}	Efficiency of a PV system
P_{DC}	DC power output
A_m	Array area

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