Soiling Effects on Solar Photovoltaics Power Plants in Three Climate Zones in Saudi Arabia

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Abstract

The Kingdom of Saudi Arabia (KSA) has a strong potential for renewable energy due to its location within the "global sun belt" range. Recently, KSA has paid more attention to this field, ultimately launching the National Renewable Energy Program (NREP) with a total capacity of up to 58.7 GW; composed mainly of solar and wind energy. Solar energy (PV), in particular, is expected to reach 40 GW by 2030. Due to the Kingdom's desert climate, one of the concerns that might affect NREP is soiling from dust, leaves, pollen, and bird droppings that ensues negative effects on solar power production. The paper will investigate the effects of soiling on solar power production through simulating real power plants using PVsyst Software in three different climate zones in Saudi Arabia. Finally, the effect of soiling on the Levelized Cost of Energy LCOE and the financial analysis are also discussed.

Keywords: Solar Energy, Saudi Arabia, Soiling, NREP, PVsyst, LCOE, Dust.

I. INTRODUCTION

Increased climate change has been considered one of the most critical concerns for the modern world. Climate change has seen countries sign agreements to mitigate the adverse effects of increased non-renewable energy sources. As the global population increases, the energy demand will rise for industrial and household use. Given that, most energy sources are dependent on non-renewable energy sources; many countries have called to adopt various renewable energy sources. According to the International Renewable Energy Agency (2022), solar photovoltaic was ranked as the most capacity added in 2021 accounting for more than 133 GW; this is a 19% increase from the year before. This indicates that solar photovoltaic is a next-generation energy source, given its high reliability during the day and ability to eliminate environmental pollution. Studies note that solar photovoltaics have zero impacts on climate change since they do not emit any greenhouse gases, which have been known as being the primary reason of global warming [1]. Despite the numerous benefits of solar photovoltaics, their efficiency can be hindered by soiling. Soiling, which is the deposition of dust, dirt, and other particles on the surface of solar panels, reduces the amount of light that can reach the panel, reducing the efficiency of the photovoltaic. The purpose of this study is to investigate the effect of soiling on solar power plants in three different climatic zones in Saudi Arabia.

Researchers investigated in 2014 the global distribution of dust particles [3]. Figure 1 shows the distribution of dust particles around the world, and they discovered that the Middle East and North Africa had the highest dust build-up. The major reason for this is that these locations have desert-like weather conditions. Another reason is the lack of or little vegetation cover exposes the surface to wind and hot sun; hence the high rate of dust particles. The researcher categorized the regions from Zone 1 to Zone 4, representing the least to worst dust accumulation.

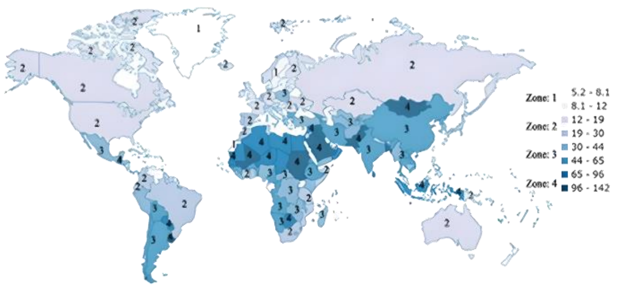

Figure 1 Global dust accumulation, Source Ghazi, Sayigh & Ip (2014)

A. Causes of Soiling

Based on studies [4-5], two major factors determine the effect of soiling on solar modules, in this case the local environment and dust properties. The dust property can comprise the weight, size, shape, and components. The term "local environment" refers to meteorological conditions and human activities occurring within a geographical region. This indicates that a horizontal surface is more likely to accommodate greater soiling than a tilted surface. [2]. Also points out that the location of the PV modules is an important

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component in determining soiling effects. The more horizontal a PV module is positioned, the more it supports dust accumulation. Figure 2 below highlights the various causes of soiling accumulation. Generally, the soiling processes on PV modules will reduce the output power by between 2% up to -50%. However, this depends on the region, climatic conditions, PV module positioning, and dust particle properties.

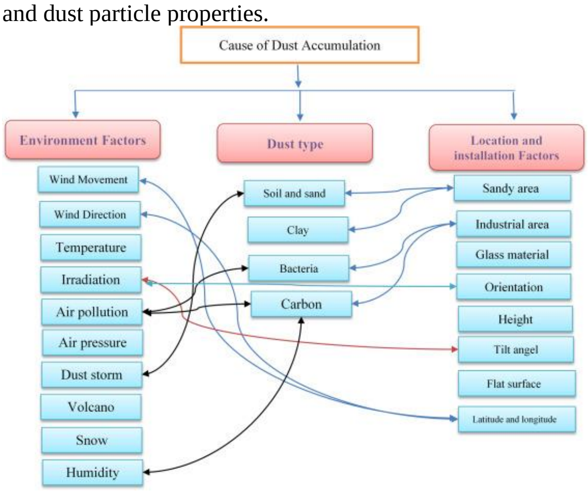

Figure 2 Causes of dust accumulation, source (Maghami et al., 2016)

B. Problem Statement

Soiling reduces the solar PV module's ability to generate energy output levels. Yet, the soiling rate has been linked to the geographical and meteorological conditions. Depending on the geographical location, the losses of power output by the solar PV modules have been noted to fall between 2-50% [2]. A lot of studies have been conducted worldwide to define the soiling effects on solar PV performance. Nevertheless, little research has been conducted to try and assess the impact of dust accumulation on two or more different geographical regions [4]. However, no research has been conducted to determine the impact of soiling in two or more different climatic regions in Saudi Arabia. Furthermore, [4] remarked that little study has been conducted in the Gulf and African countries to determine the soiling impacts on solar PV modules. From 1990 to 2017, Asian nations accounted for more than half of all studies on soiling impacts. Therefore, it is this gap in the literature that the paper seeks to fill.

C. Justification

Saudi Arabia has always been considered a desert nation. However, this does not mean it has only one climatic condition, as evidenced by Figure 3 below that the kingdom has 6 different climate zones. Saudi Arabia has significantly expanded its solar PV modules over the last few years and is one of the leaders in the Gulf region. This has seen the country setting various solar PV goals and implementing them as planned. However, the paper must establish the impact of soiling on the PV modules in three different zones in the kingdom. Therefore, the findings of this study will play a significant role in assisting solar photovoltaic companies in the kingdom in choosing the best sites for solar PV. This will be based on data gathered from specific regions distributed in the kingdom, and thus ensure that the design developed for each power plant has been adjusted to overcome the area's climatic conditions that lead to the soiling effects.

Figure 3 Climatic Zones, source (Ali et al., 2020) [6]

II. Solar Radiations in the Kingdom

The Kingdom of Saudi Arabia is characterized by high horizontal solar radiation levels, as shown in the renewable energy atlas map of the Kingdom of Saudi Arabia in Figure 4. This corresponds to the horizontal solar radiation data (GHI) monitored through the solar radiation monitoring and measurement stations established by King Abdullah City for Atomic and Renewable Energy (KACARE) at multiple sites among the Kingdom's cities.

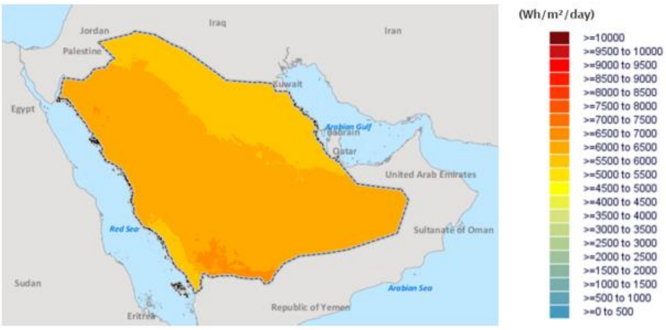

Figure 4 A Geographical map showing the average horizontal solar radiation (KACARE Atlas)

III. SOLAR PROJECTS in the Kingdom

Solar photovoltaic projects are divided into two categories, utility scale Solar PV Plant projects, which are connected to the electrical grid on high-voltage lines, and the second category, Small Scale Solar PV system projects, which are connected to the electrical grid at the medium and low voltage level in buildings and structures. The Kingdom of Saudi Arabia has prioritized permitting renewable energy sources in Vision 2030, intending for renewable energy to contribute 50% of power generation with a total capacity of up to 58.7 gigawatts. Solar photovoltaic utility scale projects represent the highest percentage of renewable energy sources targeted in the Kingdom's Vision 2030, with a total capacity of up to 40 gigawatts.

IV. Soiling in the KINGDOM OF SAUDI ARBIA

1. Dust Storms in the Kingdom

Despite the availability of solar radiation, many factors could affect a country's ability to produce solar electricity. One of these factors involves sandstorms or soiling accumulation on the surface of solar panels. General Authority for Statistics showed that the frequency of sandstorms in Saudi Arabia reached approximately 80 times per month in February 2012 the highest number of sandstorms ever recorded; Figure 5 shows the frequency of sandstorms per year starting from 2010 to 2017.

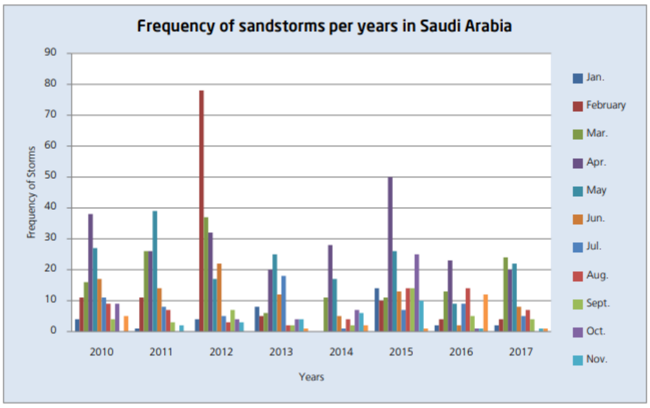

Figure 5 Frequency of sandstorms per year in Saudi Arabia (General Authority for Statistics, 2017)

2. Soiling Data Gathering

Soiling accumulation can affect the output of solar power plants, especially those that depend on solar radiation. Soiling deposited on solar panels is a major concern for plant operators because soiling particles block solar radiation. It takes time to clean up soiling and keep it soiling-free. Each solar energy investor must investigate the soiling accumulations at the site where he intends to build a solar power plant in order to avoid risks. Typically, studying the soiling effects requires data collection in one of two ways:

1) Solar panels directly: Two solar panels are placed at the same tilt angle. One of the solar panels is cleaned continuously, and the other is without any cleaning and the proportion of the difference between them is measured and known as the soiling ratio SR%.
2) Soiling measurements sensors: Measurements of soiling accumulations by placing sensors to read the accumulations on the surface of the sensor representing the state of the solar panel, and there are many commercial sensors for this purpose, but in this paper, we will explore the DustIQ Soiling device from Kipp & Zonen.

DustIQ: It is a device that contains two photodiodes with LED lights to read the soiling accumulations by knowing that from the scattered light of the LED, and it contains a solar chip to ensure that the installation of the device is equal to the solar panels. Figure 6.

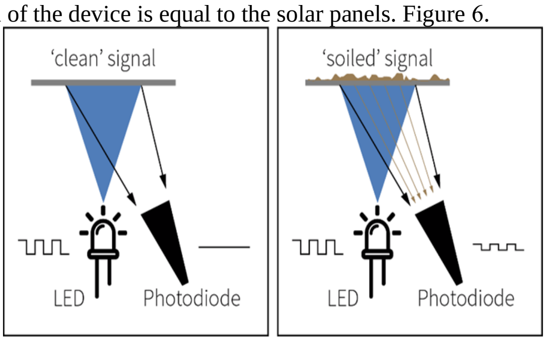

Figure 6 Diagram of DustIQ function Source, Nepal, Pramod. "Effect of Soiling on the PV Panel kWh Output." (2018)

KACARE has a solar radiation monitoring network distributed in 57 locations around Saudi Arabia and has installed soiling accumulation measuring devices (DustIQ) in 9 locations (Malhum, Mahd Al Dahab, Al Qaisumah, Rafha, Sharurah, Edabi, Sarat Abidah, Yadmah, and Lith) Figure 7.

Figure 7 Map shows the distribution of the 9 soiling accumulations devices in Saudi Arabia

The data gathered from these locations will be analyzed in the following section to determine the locations that will be studied in this paper, as well as the effect of soiling accumulation on power generation.

3. Soiling Data Analysis

The frequency of the soiling accumulation data collected is every hour from 01/06/2021 to 01/05/2022, and some data from 01/08/2021 to 01/07/2022. Therefore, an analysis was done for each data point to convert it into monthly data using the average tool in Excel, and the results were as follows:

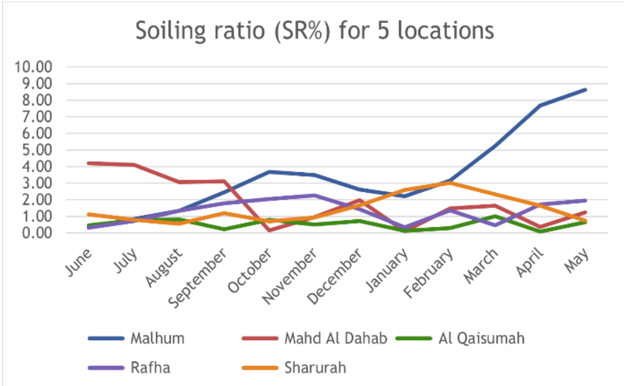

Figure 8 Graph shows the soiling ratio in 5 locations between 01/06/2021 to 01/05/2022

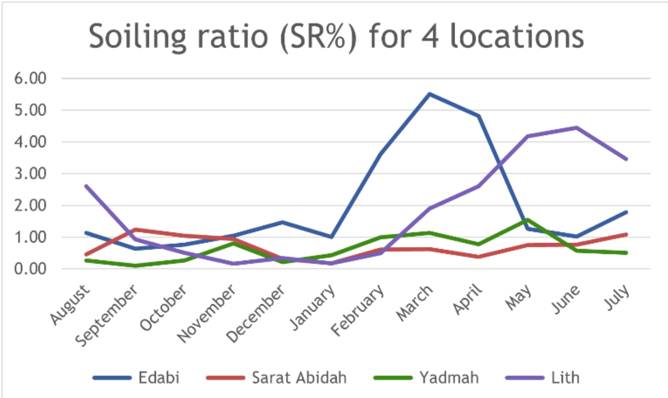

Figure 9 Graph shows the soiling ratio in 4 locations between 01/08/2021 to 01/07/2022

According to the data, the Malhum site has the most significant yearly soiling accumulation of 3.74, while Al Qaisumah has the lowest at 0.54. The remaining locations range from 0.63 in Yadmah to 2 in Edabi. Considering this, three locations were chosen for this paper: the highest, lowest, and average in Sharurah, 1.44.

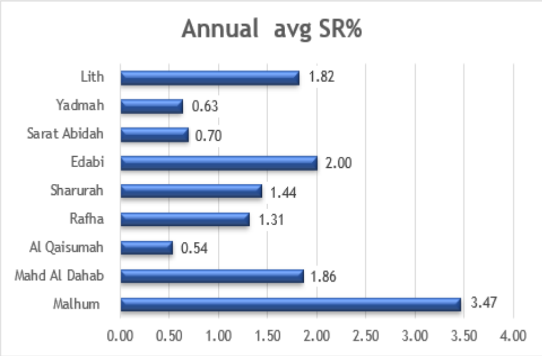

Figure 10 The annual soiling ratio in the nine locations

V. SOLAR SYSTEMS SIMULATION (PVSYS)

The power produced by a solar module is relay on the total of solar radiation, which reaches the top of the solar PV panels. Since the soiling analysis indicated three locations for modeling (Malhum, Al-Qaisumah, and Shururah), the solar radiation should be known prior to modeling, so the table below presents the global horizontal irradiance (GHI) for the locations.

Table 1 GHI For the three locations

Month	Al-Qaisumah	Malham	Shururah
kWh/m2/Month			
Jan	130.86	139.08	173.08
Feb	148.77	154.42	182.86
Mar	191.22	198.32	214.26
Apr	206.91	203.13	216.78
May	231.92	223.78	230.61
Jun	245.44	242.91	217.53
Jul	242.03	238.33	208.77
Aug	231.6	232.33	211.88
Sep	201.48	203.93	215.53
Oct	174.12	185.31	209.23
Nov	117.68	138.43	178.33
Dec	102.37	126.27	168.69
kWh/m2/Month			
Total	2224.4	2286.24	2427.55

1.Solar Systems Modeling

Modeling is carried out on three locations with identical system sizes of 30 MW, each having the same equipment specifications. Soiling data of all three locations was measured over one year with the help of soiling measurements sensors (KACARE). In addition, simulations of selected sites were carried out over the PV life span, 25 Years with and without soiling losses. Soiling is among the most important aspects influencing photovoltaic performance. The table below demonstrates the clear difference in energy numbers over the last 25 years.

Table 2 The table shows the amount of production loss due to SR%

	Al-Qaisumah		Malham		Shururah	
25 Years Generation (GWh)	Without Soiling	Soiling	Without Soiling	Soiling	Without Soiling	Soiling
	1282.06	1276.97	1404.78	1361.64	1440.75	1423.09
Loss (GWh)	5.09		43.14		17.66	
Soiling Loss %	0.40%		3.07%		1.23%	

According to the simulation, it may be stated that the best location in energy numbers is Shururah because of weather impact since the location has 2427.55 kWh/m2/ yearly, and it has an average soiling ratio. In contrast, the worst location in soiling losses is Malham at 43.14 Gwh even with those losses it is better in regards of energy output than Al-Qaisumah.

It's critical to clarify that the soiling ratio has clear affection on the energy produced and it causes huge losses for the solar system as evidenced by the simulation above, but that could be reduced by cleaning, and that comes in two ways:

- First is manual cleaning: it is the regular cleaning with water and a mop.
- Second is automated cleaning: A special electronic system cleans the solar panels automatically without any human interfaces.

In the following section, the two cleaning mechanisms will be taken into consideration in the financial analysis.

VI. SOLAR SYSTEMS ECONOMICAL ANALYSIS

Calculating the economies of solar energy is important in determining the cheapest levelized energy cost. Levelized costs of energy help in the cost comparison of solar energy to other sources of energy. LCOE measures a generator's average net present value of energy generation in its lifetime. Factors to consider while using LCOE include capital costs and operation costs. Operational costs include cleaning and on-site inspections. Other costs that could be put under consideration include system design, incentive application, installation costs, grid connection, and monitoring and control costs. When a renewable energy source such as solar energy costs reach the same level as that of the cheapest sources of energy, grid parity is achieved. When the price goes lower than the grid parity, the source of energy becomes the most intelligent choice of electrical energy (The Changing Economics of Solar Energy | EARTH 104: Earth and the Environment (Development), n.d.) [19]. For example, it is brilliant for Saudi Arabia to focus on solar energy as Shuabba and Jeddah have the lowest cost of energy in the world, which stands at $1.04 per kilowatt.

The financial analysis will be according to local and international benchmarked data as stated in table below. The capital cost (Capex), the operational costs (Opex), and the levelized cost of energy (LCOE) for all of the locations will be identified in two scenarios as mentioned in the previous section which are the manual and automated cleaning.

Table 3 Table of simulation data and benchmarked data

	Al-Qaisumah		Malham		Shururah	
	Without Soiling	Soiling	Without Soiling	Soiling	Without Soiling	Soiling
25 Years Generation (GWh)	1282.06	1276.97	1404.78	1361.64	1440.75	1423.09
25 Years Generation (kWh)	1,282,060,000	1,276,970,000	1,404,780,000	1,361,640,000	1,440,750,000	1,423,090,000
System Sizes (MW)	30					
CAPEX kW $	800 (Lazard's Levelized Cost of Energy Analysis—Version 15.0)17					
Local Benchmark						
Manual Opex per kW installed SAR	27.2 (Based on KACARE Paper) 16					
Automatic cleaning per W installed $ 18	0.03 (Based on https://www.nomaddesertsolar.com/faq.html) 18					

Based on the table above, the amount to build one solar power plant with a total installed capacity is 30 MW is 90 million SAR. Then, moving on to operation and maintenance O&M, the calculation will be as follows:

Cleaning fees = Manual/Automated cleaning (kw/year/ SAR) × Total installed capacity

The following table summarizes the prices of the two scenarios:

Table 4 Price of the two Opex scenarios

Scenario 1 (Cost per year SAR)	816,000
Scenario 2 (Cost per year SAR)	3,375,000

The most important factor to understand after calculating total Capex and Opex is how much energy would cost, which is defined by LCOE. The LCOE is determined using the formula below:

$$\text{LCOE} = \frac{\text{Capex SAR} \times \text{CRF} + \text{Opex Annual SAR}}{\text{Energy Produced kWh}}$$

CRF is the capital recovery factor, which could be identified from:

$$\text{CRF} = \frac{i(1 + i)^n}{((1 + i)^n - 1)}$$

i = Discount rate

n = Number of years

So,

$$\text{CRF} = \frac{7\%(1 + 7\%)^{25}}{((1 + 7\%)^{25} - 1)} = 0.0858$$

After applying the calculations to all locations, the LCOE is shown in the table below:

Table 5 LCOE price of the three locations

Scenarios		Al-Qaisumah SAR/kWh	Malham SAR/kWh	Shururah SAR/kWh
Without soiling	Manual cleaning	0.1528	0.1397	0.1360
	Automated cleaning	0.1986	0.1815	0.1767
With soiling	Manual cleaning	0.1534	0.1442	0.1377
	Automated cleaning	0.1994	0.1875	0.1790

High → Low

As table 5 shows the LCOE is low for all of the locations however the lowest location is Shururah since the solar radiation in the locations is over and above the other two locations, while the maximum prices are for Al Qaisumah locations. Regarding the soiling and without soiling the prices, without soiling analysis revealed it is less than with soiling, which is predictable since the power generated with soiling is not as much as the generated without soiling, but a statement could be mentioned here that the soiling issue could be overcome by the cleaning and the prices still will be low.

VII. Conclusion

Saudi Arabia has one of the highest solar irradiations in the world because of its location on the solar belt. It is generally known for its desert climate. Its southwest region is the only exemption where a mountain climate is present. Saudi Arabia, one of the leaders in solar power production in the Gulf region, has dramatically increased the number of solar photovoltaic (PV) modules it has installed in the past several years. As a result, the nation has established several solar energy goals and has carried them out as intended. Due to climate change and the country's vision to utilize solar energy, renewable energy sources, such as solar energy, have been sought out because of their competitive costs. For example, Saudi NREP announced that the project in Shuaiba, Jeddah has the lowest LCOE ($0.0104/kWh) in the world.

This paper has looked into the impact of soiling on the solarPV modules in three different climatic zones in Saudi Arabia. The kingdom is characterized as a desert, and it has high dust accumulation. The solar PV module's capacity to produce energy is significantly affected by soiling. Figure 11 below shows the price of the losses.

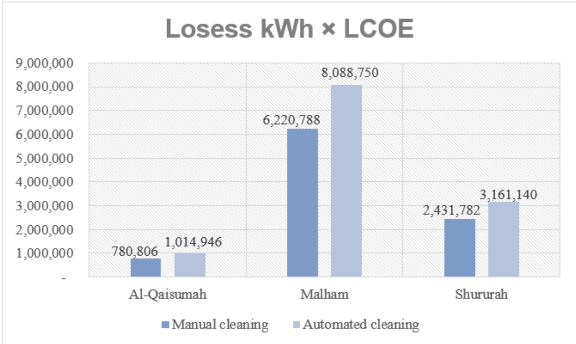

Figure 11 Price of loesses in the three locations

Because of the change in the soiling ratio, the losses varied from one location to the next, as shown in the figure above. The energy losses at the Malham site were 43.14 GWh, resulting in financial losses on the system (25 years) ranging from 6,220,788 to 8,088,750 SAR. While at the Al Qaisumah site, which has the lowest soiling ratio, energy losses were 5.09 GWh, with losses ranging from 780,806 to 1,014,946 SAR. At the same time, the Shururah site has an average soiling ratio, and the energy losses were 17.66 GWh, representing financial losses ranging from 2,431,782 to 3,161,140 SAR.

It is worth noting that the energy produced in Al Qaisumah was the lowest because solar radiation was low; however, the location was the best in terms of energy loss due to soiling accumulations. While in Sharurah, the solar radiation was good and the soiling ratio was average, which resulted in the highest amount of energy produced with decent losses reasonable of soiling. The solar radiation was good in Malham, but the soiling ratio was too high, causing significant losses in energy production.

Finally, as proven in this paper, soiling accumulation significantly reduces power generation. To mitigate the reduction, the author suggests developing a cleaning strategy for the power plant, including a frequency and methods of cleaning, as well as a corrective cleaning if anything unusual happened, such as dust storms. Nevertheless, Solar radiation is the most effective factor in power generation and the location must have high solar radiation. It is vital to note that even with the soiling losses in Sharurah location, the energy output was highest because solar radiation was strong, implying that the soiling losses may be overcome with a good cleaning method.

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