Scientific Research Publishing

Journal of Power and Energy Engineering, 2023, 11, 39-57
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

# Soiling Effect and Remedial Measures of Solar Photovoltaic System Performance in Kuwait

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**How to cite this paper:** Althuwaini, Y.E. (2023) Soiling Effect and Remedial Measures of Solar Photovoltaic System Performance in Kuwait. *Journal of Power and Energy Engineering*, **11**, 39-57.
https://doi.org/10.4236/jpee.2023.114003

**Received:** November 28, 2022
**Accepted:** April 24, 2023
**Published:** April 27, 2023



## Abstract

The Gulf Cooperation Countries have the advantages of fundamental characteristics and abundant natural resources due to the high proportion of solar radiation, which helps to expand the transition to renewable energy, especially in solar projects. The Kuwait location was chosen for this research because of its high dust levels and average daily sunshine of 9.4 hours. The soiling map of Kuwait was then created using PVsyst software. A theoretical and mathematical model for 100 MW was developed based on many environmental and technical parameters. The model was run with Kuwait parameters and 100 MW solar PV power plant capacity. The results show that more than 25% of total generated electricity could be lost annually without any mitigation strategy. Furthermore, the efficiency loss could increase by around 50% during the seasons with sandstorms and high soiling rates. Additionally, manual and automatic cleaning methods were found to increase energy production from 112,092 MWh to 207,300 MWh. Moreover, manual cleaning reduced energy costs by 4.9%, but automated cleaning resulted in a 17.34% higher energy-saving cost than a system without cleaning. In addition, when using the automatic cleaning system, the system's payback period was reduced from 9.22 to 7.86 years. Therefore, an automated cleaning system is recommended for use in Kuwait.

## Keywords

Photovoltaic Soiling Impact, Soiling Map, Mitigation Techniques, Kuwait, Payback Period

## 1. Introduction

In the solar photovoltaic (PV) global markets, the cumulative installed capacity is 892.6 GW and is expected to achieve a compound annual growth rate (CAGR) of more than 15% during 2021-2030, where China has the largest solar power capacity and generation [1].

[2] The solar energy system developed significantly in recent years, but a system's lifetime may be impacted directly or indirectly by soiling, which is the accumulation of particles on a PV module's surface. Since soiling reduces the amount of photon flux available to encapsulated solar cells, the literature demonstrates multiple effects on the performance of PV systems. The reliability of PV modules can be affected by impurities, such as airborne dust, bird droppings, and municipal sewage that unevenly deposit on their surfaces. In the past two years, the number of papers and reports on the soiling of the solar system has more than tripled, reflecting growing scientific interest and concern. As the research example shows, many types of soiling problems occur with the performance of solar PV (SPV) systems. For instance, dust affects on the performance of PV streetlights in Baghdad city [3]. They measured and analyzed the output power loss using monocrystalline PV modules. They found that soiling effects caused a 58.9% loss of total output power in three months (Feb, March, and April) for PV panels without cleaning, and for the PV panels that were cleaned weekly the output power loss of 14.1% only in the same place and period of a year.

Dust accumulation on PV panels is mainly caused by capillary, van der Waals force, electrostatic, and particle-weighing forces [4]. Moreover, relative humidity significantly affects adhesive strength; approximately 98% of adhesion in wet environments is due to capillary forces, but van der Waals forces dominate in dry environments. In addition, the surface's roughness factor is a crucial component of capillary forces, and as it increases, the capillary force weakens [5]. Two natural processes, rebound and resuspension, can remove dust from PV surfaces. The adhesion force energy of the rebound mechanism is less than the kinetic energy of the particles. Consequently, dust particles, once formed and resuspended in the atmosphere, quickly rebound off the PV module panels. The rebound process is influenced by the accumulation rate, surface orientation, surface smoothness, surface moisture, relative humidity, and PV module temperature. As shown in **Figure 1** illustrates these forces and important factors which have an impact on each force component.

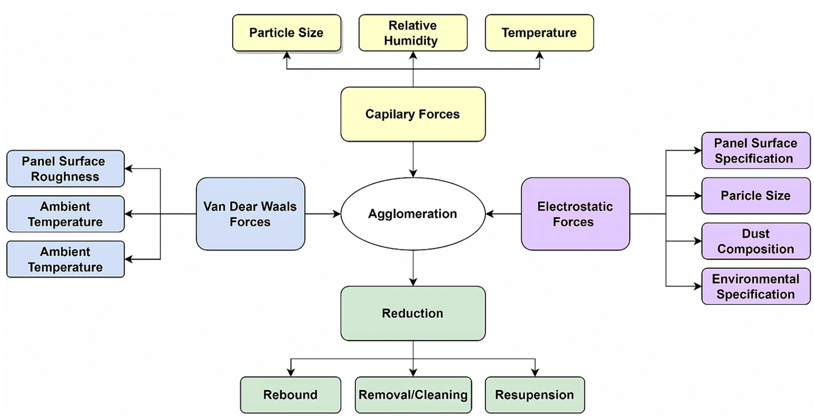


**Figure 1.** Main causes of agglomeration of dust on PV panels [4].

Several methods have been adopted and investigated to mitigate dust from PV panels [6] [7] [8]. Depending on their nature, these strategies fall into two broad categories prevention and restorative, as shown in **Figure 2**. Prevention methods include the smart design of PV systems and self-cleaning methods. Restorative methods are divided into natural, manual, and automatic [9]-[14].

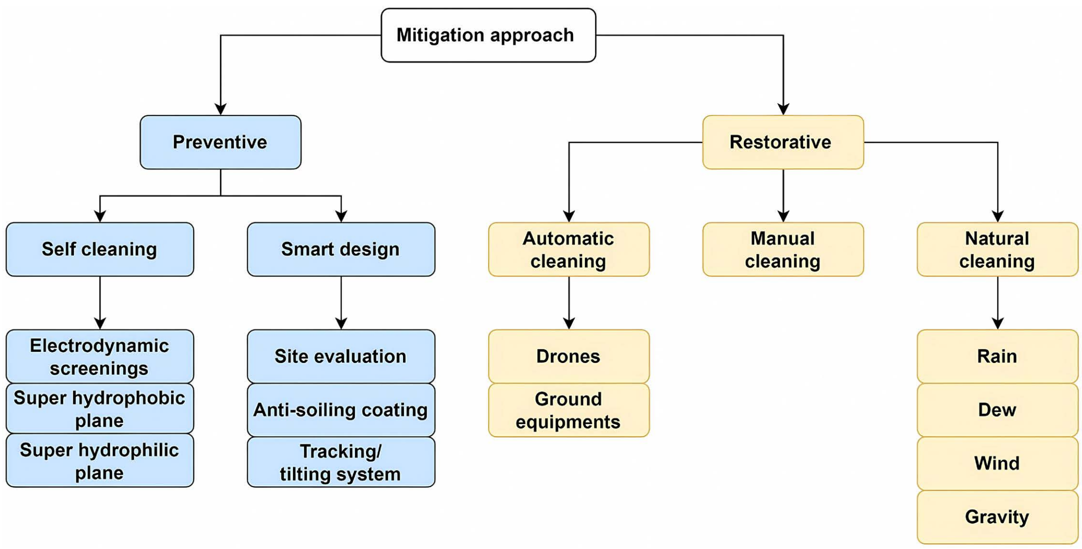


**Figure 2.** Dust soiling mitigation strategies [6] [7] [8].

This passive technique can be used for two purposes: controlling dust and avoiding pollution. Coating the PV surface and then using motorized screens to keep dust away is part of the self-cleaning process. Even though automated methods have become standard, third, periodic hand cleaning of PV modules is still performed. This is true even if many tasks are now performed automatically. In this sense, it's similar to cleaning glassware or dishware. The module's surface is cleaned using a variety of brushes and towels. Even the deepest entrenched stains may be eradicated using this method.

The automated system aims to respond rapidly, be highly stable, be self-sufficient, use little electricity, and reduce running expenses. More frequent cleaning of the module is required at initially, but after some time has passed, less frequent cleaning will be necessary. In spite of the manufacturer's claims, there's always a chance that the gadget won't last as long as advertised or won't work as well as advertised under real-world conditions.

This tactic has only recently gained traction, but it is already the focus of extensive research in universities around the world. Bright technology claims that a robotic cleaning system developed by SOL can eliminate more than 99% of the dust accumulated in a large solar farm, thereby increasing the farm's efficiency by 7% - 15%. Because of the grave consequences, this needs careful monitoring [15]. Many locations in the world have the advantage of high solar radiation, which helps them to install photovoltaic power plants to harvest solar energy; however, some disadvantages factors should consider, as shown in **Figure 3**.

There are factors responsible for PV panel efficiency degradation; it's essential to consider the pros and cons of all factors, such as environment, PV construction, installations, operation, and maintenance, therefore, finding appropriate solutions to increase solar panel efficiency [16].

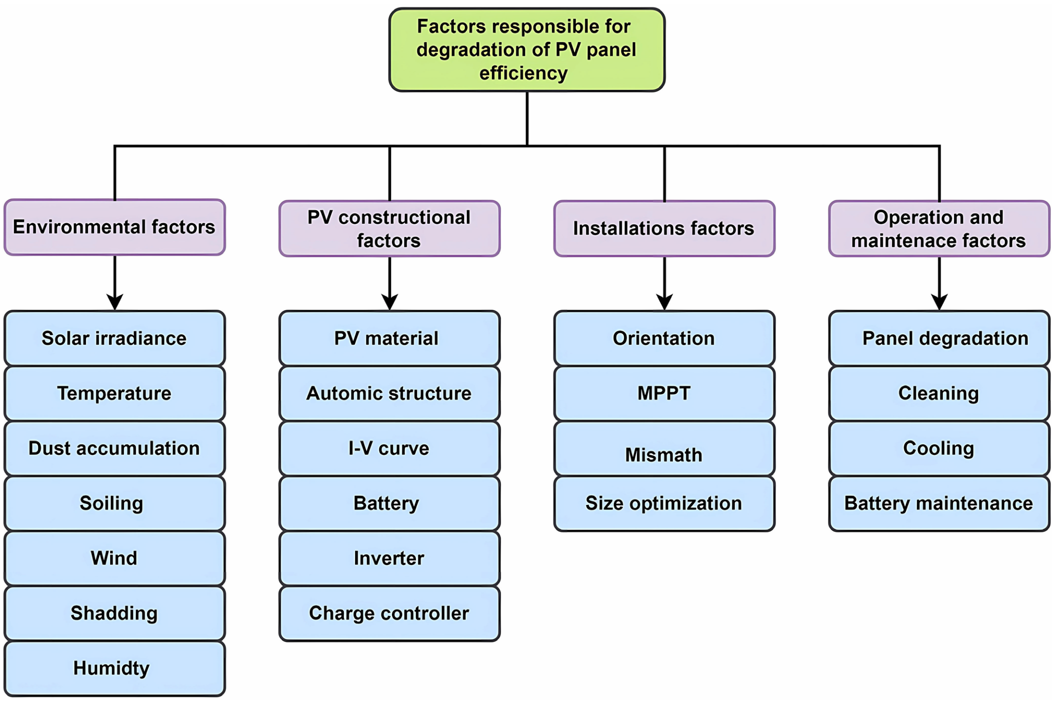


**Figure 3.** Factors that affect PV system efficiency [16].

## Kuwait Weather Conditions

Sandstorms and sand blizzards are common in Kuwait during the summer, winter, and early spring. A Mediterranean depression's passage in the region brings with it strong, southeasterly prevailing winds, which can bring about severe weather. Heavy dust storms frequently occur throughout the afternoons and nights throughout the month of April, drastically decreasing visibility. Such storms occur frequently. It is possible for strong dust storms to be whipped up by southeasterly winds in the spring, but these events usually only last a day or two before being wiped out by rain [17] [18] [19]. Dust storms, which occur during the summer, are caused by the monsoon because of the prevailing northwesterly dry and warm winds (known as Simoom). A rise in summer dust storms, especially in June and July [20], can be attributed to the interconnectedness of local and global climates. Located south of the Mesopotamian floodplain in the northern Arabian Gulf, Kuwait is composed of several layers of mud and siltstone. Due to the area's low elevation, absence of vegetation, and fine-grained soil, as well as its frequent interactions with high winds and turbulence, dust storms are a common occurrence. [21] According to the Metrological Department of the Directorate General of Civil Aviation in Kuwait (MDDGCA), the average of amounts for dust falling over Kuwait is 20 - 60 tons/km$^2$/month, which is reaching 1 million tons per year, where measured during 12 years from 2000 to 2012. [22] There is an experimental study has been done in Kuwait to get results, and the effects of dust on the transparency of a glass plate revealed for 38 days found the following outcomes. For a tilt angle of 0˚ (horizontal), the decrease in transmissivity was around 64%; for tilt angles of 30˚, 45˚, and 60˚, the decrease in transmissivity was around 38%, 30%, and 17%, respectively. Where this exposed the significant effect dust has on decreasing transparency and the powerful dependence on the tilt angle of the surface. [23] Other studies have shown that Kuwait is exposed to 25% of the days of the year, where approximately 40% of Kuwait's dust comes from Iraq, which costs approximately KWD 190 million (USD 622.54 million) in financial losses due to dust per year. [24] Further studies, The main conclusion in Kuwait was that need increasing afforestation in the Kuwaiti desert decreases the effect of dust, where the average loss in efficiency from the expected used PV panels is around 45%; therefore, the expectant energy fundamental loss due to vegetation change is approximately 2025MW with (USD 283,500) as annual cost taking in consideration the local price of 0.14 USD/kWh in Kuwait based on the National Bank of Kuwait (NBK).

[25] Further studies about dust falling over several areas were monitored and analyzed in various locations in Kuwait. The information was extracted through visible satellite images from the year 2000 to 2010 to determine the sources and paths of the main dust storms near Kuwait. These images identified five main areas: 1) The southwestern desert of Iraq; 2) Mesopotamia floodplain in Iraq; 3); Northeastern desert of Saudi Arabia; 4) Drained marshes of Iraq "Ahwar"; 5) The dry marshes of Iran. In addition to the above, the local locations in Kuwait exposed a high percentage of dust annually as following: 1) Bubiyan island (112 tons\km$^2$); 2) Warbah island (58 tons\km$^2$); 3) Al Jahra city (36 tons\km$^2$); 4) Al Liyah area (31 tons/km$^2$); 5) Sabah Al Ahmad Natural Reserve (2 tons/km$^2$). The results of the volumetric analysis showed that the sand volume represents 37% of the average total volume of dust samples, while the clay particles represent 63%. Quartz represents the highest proportion of minerals and ranges between 35% - 52%, with an average of 44%, as the percentage of quartz showed an increase with a decrease in the rate of carbonates in the summer periods as a result of the winds in the region. In addition, the analysis of the total three-dimensional area of dust grains in Kuwait revealed a significant difference with dust regionally and globally and its similarity with dust in locations in the Arab Gulf countries such as Bahrain and (UAE, specifically in Dubai and Al Ain) [25].

## 2. Literature Review

Studies and evaluations of solar PV systems have revealed that environmental and meteorological factors should be considered in order to maximize their performance and efficiencies. Debris, like dust, bird feces, soil, and snow, can build up on the surfaces of PV modules, causing losses inefficiencies and shortening the lives of the panels. Conducted an experiment to determine how smog-filled air impacts solar panel efficiency. The experiment that was carried out by took place in Athens, well-known for its high population density and levels of air pollution. Over two months, they monitored and recorded the effects urban air pollution had on the electricity produced by PV panels. No cleaning of the panels before or after the study was carried out. The results showed a yearly loss of around 40V/kWp due to the decreased energy production of the PV panels, which is approximately 1% of the current turnkey-specific price of domestic PV generators [26].

In a relevant study, researchers working in the field of renewable and sustainable energy conducted an experiment exposing PV modules to various major air pollutants, including four forms of dust. The objective of the laboratory experiment was to recreate the environmental conditions that prevail in Oman to achieve corresponding panel deterioration. Because of the sand accumulation, the voltage dropped by 4.7%, and the fly ash accumulation caused the voltage to drop by another 25% [27]. Another physicist assessed the effect of dust pollution on the efficiency of solar arrays in Saudi Arabia. The experiment out showed that the buildup of sand from the desert over eight months resulted in a 32% loss in electricity generated [28]. Similarly, sand deposition in Kuwait resulted in a 17% decrease in the energy efficiency of PV modules in just six days, according to research [29]. The majority of research in this area has focused on how dust affects ground-mounted PV arrays on a broad scale. Few studies in urban areas that are highly polluted and densely populated (*i.e.*, metropolitan zones) have looked at dust buildup on PV panels mounted on building rooftops. Therefore, we need to conduct field experiments that analyze the influence of dust in settings where solar panels are actually deployed to achieve a complete understanding of how the performance of solar panels is impacted by pollution in urban areas.

## 3. Methodology

### 3.1. Kuwait Climate

As previously stated, environmental properties and several geographical factors impact soiling deposit rates and, consequently, PV panel performance. Kuwait's climate makes the country extremely prone to dust and high soiling rates. Moreover, the intensity of the soiling and the dust's chemical and physical properties vary significantly during the year [19]. [30] Seasonal soiling maps might be helpful for estimating soiling rates. This helps the selection of the strategy that will minimize soiling prior to panel cleaning. The soiling factor and the frequency of days with a high dust content in Kuwait were used as input data for this simulation experiment. **Table 1** shows that the environmental conditions have the potential to influence the rates of soiling deposits and consequently, the performance of PV panels. Kuwait's desert climate causes a lot of dirt and dust to accumulate quickly [31]. Additionally, in recent studies, the average total yearly dusty days in Kuwait are 255 days, which absolutely will affect harvesting solar energy in the region, especially when not using advanced therapeutic methods that mitigate dust effects; for this reason, the location of Kuwait is idealistic for investigating the high impact of dust and weather challenges on the generation of solar energy generation [32].

**Table 1.** "Average soiling factor and the number of high dusty days per month in Kuwait" [31].

| Month | "Soiling factor $\beta$" | "Dusty days/month" | Days with high *AOD* |
|---|---|---|---|
| Jan | $9.99 \times 10^{-5}$ | 7 | 4 |
| Feb | $9.66 \times 10^{-5}$ | 12 | 7 |
| Mar | $8.53 \times 10^{-5}$ | 18 | 13 |
| Apr | $29.17 \times 10^{-5}$ | 13 | 13 |
| May | $17.52 \times 10^{-5}$ | 22 | 13 |
| Jun | $7.68 \times 10^{-5}$ | 19 | 18 |
| Jul | $3.41 \times 10^{-5}$ | 12 | 15 |
| Aug | $4.05 \times 10^{-5}$ | 17 | 10 |
| Sep | $10.70 \times 10^{-5}$ | 11 | 4 |
| Oct | $12.05 \times 10^{-5}$ | 2 | 8 |
| Nov | $10.96 \times 10^{-5}$ | 4 | 2 |
| Dec | $7.16 \times 10^{-5}$ | 7 | 1 |
| **Avg** | $\mathbf{10.91 \times 10^{-5}}$ | **12.00** | **9.00** |

## 3.2. Derivation of Power Loss

In many counties, there are a high percentage of dust and soiling, which is a critical factor affecting solar cells' efficiency; where dust accumulation on the panels reduces the photovoltaic performance and energy production, therefore very important to clean photovoltaic (PV) panels to limit losses due to dust and soiling. Logically cleaning the solar panels will cost money, but the losses due to dust and soiling also will cost the owner reduced revenue and output power.

The power loss of all soiled PV panels at a given fixed tilt angle between 0˚ and 90˚ was calculated relative to an identical clean solar panel adjusted at the same tilt angle using the following formula [16] [33].

$$E_l(t) = \frac{P_{\text{clean}} - P_{\text{soiled}}}{P_{\text{clean}}} \times 100 \quad (1)$$

where $P_{\text{clean}}$ is the amount of power produced by a clean panel and $P_{\text{soiled}}$ the output power of a dusty. Different definitions for the soiling rate are available in the literature; in the current study, $R_{\text{soil}}$ is designated by the soiling rate on the solar panel on each day of the month.

$$R_{soil} = \frac{\mathrm{d}E_l(t)}{\mathrm{d}t} \quad (2)$$

The particle and dusting specifications were employed to derive the cleaning schedule. The loss factor $\beta$ is an essential parameter required to develop the cleaning schedule model that is determined through curve fitting of the soiling data. The following are the steps that need to be taken in order to calculate the soiling loss factor by the equation below:

$$\beta = \frac{\mathrm{d}}{\mathrm{d}t}\left(\ln\left(1-E_l\left(t\right)\right)\right) \tag{3}$$

Two parameters need to be calculated for the cost of energy lost due to soiling $V_{sl}$ and the price of generated energy throughout a cleaning interval $V_p$ as per the below equations:

$$V_{sl} = \int_0^{tc} T_r\left(t\right)\times P\left(t\right)\times E_l\left(t\right)\mathrm{d}t \tag{4}$$

$$V_p = \int_0^{tc} T_r\left(t\right)\times P\left(t\right)\times\left(1-E_l\left(t\right)\right)\mathrm{d}t \tag{5}$$

The variable in the equations below indicates the electricity tariff $T_r\left(t\right)$, where $P\left(t\right)$ is the overall rated power capacity and the amount of time that elapses between cleaning cycles, $t_c$ are all intervals of cleaning cycles.

$$V_{sl} = T_r \times P\left(t_c + \frac{e^{-\beta t_c}-1}{\beta}\right) \tag{6}$$

$$V_p = T_r \times P\left(\frac{e^{-\beta t_c}-1}{\beta}\right) \tag{7}$$

The cumulative economic value of the energy lost due to soiling could be found using soiling loss $V_{sl}$ plus the cost of cleaning or mitigation processes $V_{cl}$. The relation's derivative was found, indicating the minimum energy loss due to the soiling:

$$\frac{\mathrm{d}}{\mathrm{d}t_c}\left(\frac{V_{sl}+V_{cl}}{V_p}\right) = 0 \tag{8}$$

The solution of Equation (8) represents the derived model:

$$\frac{V_{sl}+V_{cl}}{V_p} = \frac{E_l\left(t_c\right)}{1-E_l\left(t_c\right)} \tag{9}$$

**Table 2** shows the input parameters and assumptions for this study [34].

**Table 2.** Input parameters and assumptions for this study [34].

| Description | Value |
| --- | --- |
| Power plant capacity (MW) | 100 |
| Feed-in tariff ($/Kwh) | 0.054 |
| Average daily sunshine (h) | 9.4 |

### 3.3. Mathematical Modeling of 100 MW PV System at Al Wafra, Kuwait

[13] [33] The following formulas were incorporated into the PV model as listed

in Table 3:

Table 3. Formulas used in the PV model [13] [33].

| Description | Formulas | Equation Number |
|---|---|---|
| Energy Capacity per day | $= TC \times AH$ where $TC$ is the total capacity and $AH$ is the average hours per day for solar radiation. | (10) |
| Energy generation per day | $= \frac{\text{Energy capacity per day}}{SR}$ where $SR$ is the average solar radiation per day. | (11) |
| Solar Panel Energy needed | $= \text{Energy generation per day} \times \text{Panel efficiency}$ | (12) |
| Number of solar panels | $= \frac{\text{Solar panel energy needed}}{\text{Single solar panel power}}$ | (13) |
| Number of panels for series connection | $= \frac{\text{Inverter maximum input voltage}}{\text{Solar panel Voc}}$ | (14) |
| Total number of strings | $= \frac{\text{Total number of solar panels}}{\text{Number of solar panels in each series connection}}$ | (15) |
| Total number of inverters | $= \frac{\text{Total energy}}{\text{Inverter rating}}$ where the inverter rating is in KVA. | (16) |
| power generation per year (kWh) | $GP = SR \times CA \times AF \times \eta$ where $GP$ is the, $SR$ is the solar radiation, $CA$ is the total area, $AF$ is the area factor, and $\eta$ is the panel efficiency. | (17) |
| Capital recovery factor (CRF) | $= \frac{i \times (1+i)^n}{\left[(1+i)^n - 1\right]}$ | (18) |

[35]-[40] In this study, six different scenarios have been analyzed, as shown in Table 4:

Table 4. Solar panel types with price per unit estimated in the market in 2023 [35]-[40].

| Scenario | Pmax W | Panel Model | Price per unit | Ref |
|---|---|---|---|---|
| 01 | 250 | EG-250P60-C | $125 | [35] |
| 02 | 310 | JAM60S01 | $142 | [36] |
| 03 | 350 | LG35ON1C | $162 | [37] |
| 04 | 410 | PERC144 | $168 | [38] |
| 05 | 460 | JAM72S20 | $218 | [39] |
| 06 | 560 | TSMDE19 | $275 | [40] |

Table 5 listed the parameters of the solar panel calculations [13] [33] [35]-[41].

Table 5. Parameters of the solar panel calculations [13] [33] [35]-[41].

| Solar panel calculations | | Source |
|---|---|---|
| Total capacity of PV power plant (MWp) | 100 | Equation (12) |
| Average solar irradiation (h) | 10 | [29] |
| Total energy capacity per day | 10 × 100 MWp = 1000 MWp = 1,000,000,000 Wh/day | Equation (12) |
| Solar radiation (kWh/m²/day) | 4.81 | [30] |
| Energy generation per day GWh/day | 182.81 | Equation (13) |
| **Inverter specifications** | | |
| Input voltage (V) | 900 | |
| MPP voltage range (V) | 450 - 900 | |
| Minimum input voltage (V) | 300 - 750 | |
| Maximum input current (A) | 25 | |
| Maximum AC power (kVA) | 500 | [31] |
| Nominal AC voltage (V) | 120 - 280 | |
| Frequency (Hz) | 50 - 60 | |
| Maximum output current (A) | 22 | |
| Efficiency | 98% | |

## 4. Results and Discussion

### PVSyst Modeling

A 100 MW photovoltaic power plant was modeled in PVsyst to explore the balances and main results for an entire year, as shown in **Table 6** [42]. In addition, the findings of the performance ratio were collected to evaluate the soiling, and its effect on the system's efficiency is displayed in **Figure 4** [42]. Six PV module scenarios were examined. For 250 W, 582,318 solar panels were needed, decreasing to 259,963 for 560 W in **Table 7** [13] [33] [35]-[41].

Table 6. Balances and main results for a 100 MW PV power plant in Al Wafra, Kuwait [42].

| Month | GlobHor kWh/m² | DiffHor kWh/m² | T_Amb ˚C | GlobInc kWh/m² | GlobEff kWh/m² | Earray MWh | E_Grid MWh | PR Ratio |
|---|---|---|---|---|---|---|---|---|
| **January** | 111.6 | 45.6 | 12.62 | 169.6 | 161.6 | 12,249 | 11,905 | 0.702 |
| **February** | 122.2 | 57.8 | 15.26 | 157.8 | 150.5 | 11,071 | 10,079 | 0.639 |
| **March** | 149.5 | 84.0 | 20.89 | 162.4 | 153.9 | 10,866 | 10,540 | 0.649 |
| **April** | 178.2 | 92.3 | 26.41 | 184.4 | 175.1 | 11,092 | 10,779 | 0.585 |
| **May** | 200.8 | 104.9 | 33.47 | 200.2 | 190.1 | 9695 | 9405 | 0.470 |
| **June** | 215.4 | 105.7 | 37.43 | 211.4 | 200.8 | 8036 | 7781 | 0.368 |
| **July** | 210.9 | 101.9 | 39.48 | 208.7 | 198.3 | 7305 | 7056 | 0.338 |
| **August** | 198.1 | 97.2 | 38.97 | 202.0 | 192.0 | 7268 | 7035 | 0.348 |

Continued

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **September** | 174.0 | 73.8 | 34.70 | 186.7 | 177.3 | 8538 | 8287 | 0.444 |
| **October** | 144.7 | 67.2 | 29.18 | 177.8 | 168.8 | 9889 | 9615 | 0.541 |
| **November** | 112.4 | 48.5 | 19.84 | 160.5 | 153.5 | 10,760 | 10446 | 0.651 |
| **December** | 101.1 | 45.2 | 14.41 | 154.9 | 148.1 | 11,103 | 9073 | 0.586 |
| **Year** | **1919.0** | **924.2** | **26.96** | **2176.3** | **2070.0** | **117,870** | **112,001** | **0.515** |

(Legends: GlobHor: Global horizontal irradiation; DiffHor: Horizontal diffuse irradiation; T_Amb: Ambient Temperature; GlobInc: Global incident in coll. Plane; GlobEff: Effective Global, corr. for IAM and shadings; Earray: Effective energy at the output of the array; E_Grid: Energy injected into grid; PR: Performance Ratio).

**Table 7.** Solar panel calculations for the six studied scenarios [13] [33] [35]-[41].

| Description | Scenario 01 | Scenario 02 | Scenario 03 | Scenario 04 | Scenario 05 | Scenario 06 |
|---|---|---|---|---|---|---|
| Solar panel energy (W) ($\beta$ = 30%) | 207,900,208 × 0.7 = 145,579,524 | 207,900,208 × 0.7 = 145,579,524 | 207,900,208 × 0.7 = 145,579,524 | 207,900,208 × 0.7 = 145,579,524 | 207,900,208 × 0.7 = 145,579,524 | 207,900,208 × 0.7 = 145,579,524 |
| Number of solar panels | 145,579,524 ÷ 250 W/panel = 582,318 | 145,579,524 ÷ 310 W/panel = 469,610 | 145,579,524 ÷ 350 W/panel = 415,940 | 145,579,524 ÷ 410 W/panel = 355,072 | 145,579,524 ÷ 460 W/panel = 316,477 | 145,579,524 ÷ 560 W/panel = 259,963 |
| **Solar panel specification** | | | | | | |
| Maximum power (W) | 250 | 310 | 350 | 410 | 460 | 560 |
| Tolerance (%) | 0 - 3 | 0 - 3 | 0 - 3 | 0 - 3 | 0 - 3 | 0 - 3 |
| Voc (V) | 37.29 | 40.30 | 41.30 | 48.90 | 50.01 | 38.3 |
| Isc (A) | 8.81 | 9.91 | 10.61 | 10.70 | 11.45 | 11.45 |
| Maximum power voltage (V) | 30.34 | 32.84 | 35.30 | 40.65 | 42.13 | 32 |
| Maximum power current (A) | 8.24 | 9.44 | 10.61 | 10.10 | 10.92 | 17.49 |
| Module efficiency (%) | 15.3 | 19 | 20.4 | 20.4 | 20.7 | 21.4 |
| **Series panel calculations** | | | | | | |
| Number of panels connected in series for one string | 900 V ÷ 37.29 V = 24 | 900 V ÷ 40.30 V = 22 | 900 V ÷ 41.30 V = 22 | 900 V ÷ 48.90 V = 18 | 900 V ÷ 50.01 V = 18 | 900 V ÷ 38.3 V = 24 |
| **Number of strings calculations** | | | | | | |
| Number of strings needed | 582,318 ÷ 24 = 24,263 | 469,610 ÷ 22 = 21,346 | 415,940 ÷ 22 = 18,906 | 355,072 ÷ 18 = 19,726 | 316,477 ÷ 18 = 17,582 | 259,963 ÷ 24 = 10,832 |
| **Inverter calculation** | | | | | | |
| Number of Inverters needed | 145,579,524 ÷ 500,000 = 291 | 145,579,524 ÷ 500,000 = 291 | 145,579,524 ÷ 500,000 = 291 | 145,579,524 ÷ 500,000 = 291 | 145,579,524 ÷ 500,000 = 291 | 145,579,524 ÷ 500,000 = 291 |
| **Solar panel cost estimation** | | | | | | |
| Cost of PV panels | $125 × 582,318 = $72,789,750 | $142 ×469,610 = $66,684,620 | $162 ×415,940 = $67,382,280 | $168 × 355,072 = $59,652,096 | $218 × 316,477 = $68,991,986 | $275 × 259,963 = $71,489,825 |

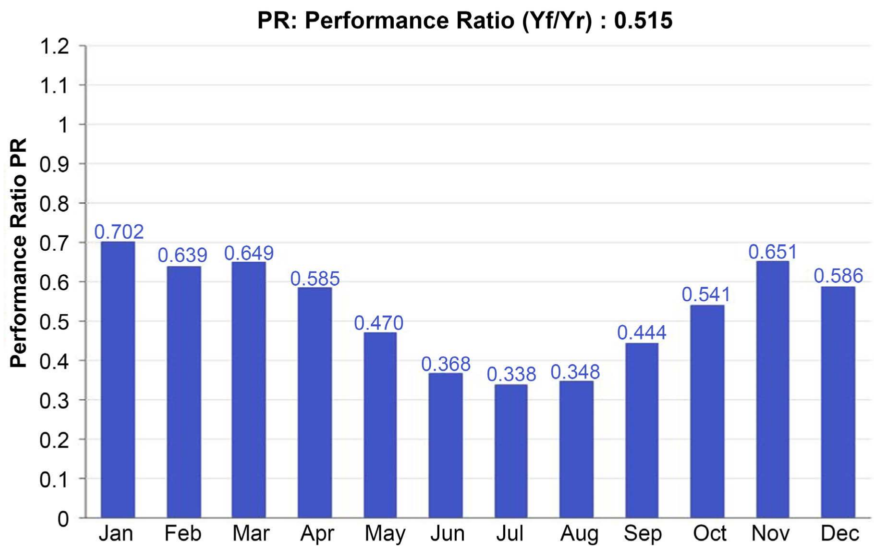


**Figure 4.** Performance factor for a 100 MW power plant in Al Wafra, Kuwait [42].

As shown in **Figure 4**, [42] The proportion of soiling varies from year to year, hovering around 50% during the dusty season and averaging 25.4%. We can consider not installing any cleaning or tracking systems. This can assist in analyzing the various losses that are to be encountered while installing the PV plant, therefore, can be considered or reduced it. Additional details on the system loss parameters in the simulation are shown in **Table 8** [42].

**Table 8.** PV losses parameters for the 100 MW simulation [42].

| Variable | Change (%) | Energy after (kWh/m$^2$) |
|---|---|---|
| Global horizontal irradiation | | 1919 |
| Global incident in coll. plane | 13.04 | 2169 |
| Far shadings: irradiance loss | −0.35 | 2093 |
| IAM factor on global | −1.60 | 2059 |
| **Soiling loss factor** | **−3** | **1997** |
| Effective irradiation on collectors | | 1997 |
| Global effective energy | | 1997 |
| On an area of 505,687 m$^2$, total energy on collectors | 207,300 MW | |
| Efficiency at STC | 19.80% | |
| **Array losses** | **Change (%)** | **Energy after (MWh)** |
| Array nominal energy | | 207,300 |
| PV loss due to irradiance level | −0.56 | 207,184 |
| PV loss due to temperature | −11.86 | 182,611 |
| Spectral correction for amorphous | −0.60 | 181,040 |
| Shadings: electrical loss | −1.34 | 178,614 |
| Optimizer efficiency loss | −0.68 | 178,492 |

Continued

| | | |
|---|---|---|
| Module quality loss | −2.50 | 174,030 |
| Mismatch loss, modules, and strings | −2.10 | 170,375 |
| Ohmic wiring loss | −0.73 | 172,350 |
| Array virtual energy at MPP | | 148,308 |
| **System losses** | **Change (%)** | **Energy after (MWh)** |
| Inverter loss during operation | −2.31 | 68,417 |
| Inverter loss over nominal inv. power | 0.00 | 68,417 |
| Inverter loss for the max. input current | 0.00 | 68,417 |
| Inverter loss over nominal inv. Voltage | 0.00 | 68,417 |
| Inverter loss due to power threshold | 0.44 | 64,417 |
| Inverter loss due to voltage threshold | 0.00 | 64,417 |
| Night consumption | −0.01 | 64,417 |
| Available energy at the inverter output | | 64,417 |

One of the most pressing research needs is the exploration of methods to reduce soiling and dust deposition, which are responsible for a considerable portion of Kuwait's overall power deficit. Equation (9) below depicts the model used to assess the soiling loss and cleaning benefits. Two different methods of cleaning the model power plant were investigated and compared. Table 9 dissects the operations of both hand washing and machine cleaning [13] [33].

Table 9. Cleaning cost calculations for 100 MW power plant for 2021 [13] [33].

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Power plant capacity (MW) | 100 | Plant's land area ($m^2$) | 1059252.5 |
| Module efficiency | 14% | Labor rate ($/h) | 6 |
| Labor rate ($/yr) | 850 | Supervisory labor rate ($/h) | 12 |
| Labor hours/year per laborer | 1750 | Labor hours/day | 5.1 |
| Supervisory labor rate ($/yr) | 1700 | Water needed (L) | 423,701 |
| No. of laborers per supervisor | 20 | Cleaning time (h) | 235.39 |
| Electricity Price ($/kWh) | 0.054 | | |
| Cost of water ($/L) | 0.0024 | | |
| Cost of other materials ($/m) | 0.0054 | | |
| **Manual** | | **Automatic** | |
| Cleaning time per panel (min) | 0.5 | Initial investment ($) | 91,000 |
| Water usage (L/$m^2$) | 0.4 | Water usage (L/$m^2$) | 0.6 |
| | | O&M costs per hour ($) | 7 |
| | | Cleaning rate ($m^2$/h) | 4500 |
| | | Lifetime (yr) | 10 |
| | | Operators per machine per shift | 1 |

Continued

| Cleaning cost calculations | | Cleaning cost calculations | |
|---|---|---|---|
| Total labor hours per cleaning cycle | 3000 | Total labor hours per cleaning cycle | 160 |
| | | Allocated expenses ($/h) | 3.2 |
| **Total cost per cleaning cycle** | | **Total cost per cleaning cycle** | |
| Labor ($) | 18000.00 | Labor ($) | 960.00 |
| Water ($) | 1016.88 | Water ($) | 1525.32 |
| Other material ($) | 3827.00 | Other material ($) | 1100.00 |
| | | Allocated capital cost ($) | 512.00 |
| **Total ($)** | **22843.88** | **Total ($)** | **4097.32** |
| **Cost per cleaning cycle ($/MW)** | **228.44** | **Cost per cleaning cycle ($/MW)** | **40.97** |

Based on these cleaning costs, the optimum cleaning cycle time for maximizing the power plant revenue is determined using Equation (9), as shown in Figure 5 [13] [33].

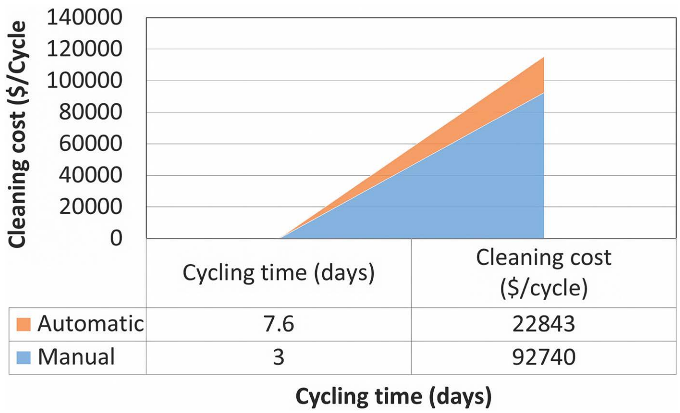


Figure 5. Variation of cleaning cost and cycling time [13] [33].

Figure 5 shows the change in cleaning cost and cycle time between cleanings for manual and automatic PV panel cleaning systems [13] [33]. The automatic cleaning system costs $22,843.88, more than 4.5 times that of the manual cleaning system. The manual cleaning system had a shorter cycle time of 3 days, a 126% reduction over the automatic cleaning system. From these data, we cannot determine which one is best for a 100 MW PV plant because the cycle time is inversely proportional to the total cleaning cost, and the cleaning cost per cycle is directly proportional to the total cleaning cost. Therefore, the energies generated by uncleansed, manually cleaned, and automatically cleaned PVs were evaluated using PVSyst to determine the revenue. The total cleaning cost for manual and automatic cleaning was then calculated. Finally, the energy savings costs and payback periods for uncleansed, manually cleaned, and automated cleaning systems were estimated.

**Figure 6** shows the change in power generations, collection losses, and system losses for uncleaned, manually cleaned, and automatically cleaned systems. The total collection loss, or PV array loss, due to dust and shading is 2.73 kWh/day, where the energy production is 3.07 kWh/day after losses, and system losses are 0.16 kWh/day. Total cleaning costs for manual cleaning systems were 130% higher than for automatic cleaning systems [42].

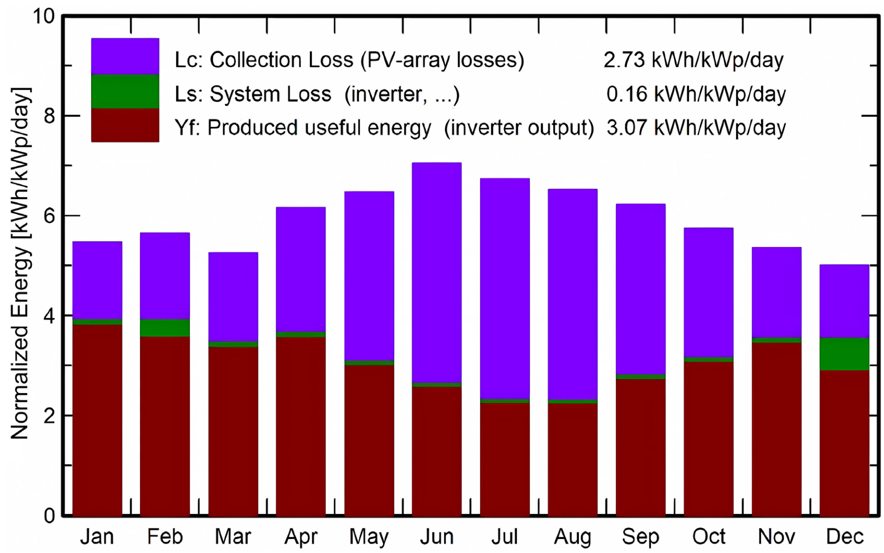


**Figure 6.** Normalized production and loss factors [42].

## 5. Conclusions

The MENA region has enormous solar energy potential. However, its unique geography and climate cause considerable soiling, which affects photovoltaic (PV) system performance. This makes it a big challenge for stakeholders to build PV installations. Dust deposition on PV modules decreases PV system performance quickly, attracting global study interest. This study provides an overview of the characteristics of dust and its particles, its origins, and how it affects PV systems in the Kuwait region. In addition, this study examines the Kuwaiti PV system's dust effects. Dust-producing components are also considered. Dust can damage solar modules; hence several studies and methods for reducing dust collection are discussed.

The review found that dust degrades PV modules and is controlled by several factors. The review also found flaws in all risk reduction strategies, which were unsatisfactory. An effective approach must consider location and environmental considerations. One of these risk reduction measures must be used regularly to improve PV module performance and maintain them. According to modeling, soiling causes 25.4% of system losses over one year, more than 42% during dusty season. We mathematically modeled a 100 MW PV system in Al Wafra, Kuwait. Six PV module scenarios were examined. For 250 W, 582 318 solar panels were needed, decreasing to 259,963 for 560 W. This article also presents PVsyst simulation findings for a 100 MW PV system.

Researchers from the Gulf Cooperation Council (GCC) and the Far East countries have concluded that the production of clean PV panels is critical. Researchers working on PV systems are aiming to improve the low reliability and poor performance of these systems while mitigating the associated high initial costs and ongoing maintenance associated. They need to carry out more in-depth examinations so that we can lessen our dependency on conventional cleaning methods that require water use. As a result, we can become less reliant on these practices. In addition, continuing to make efforts in this area can help maintain PV panel efficiency. Further developments of artificial intelligence-based cleaning models and intelligent cleaning procedures are strongly urged. Ideally, these models and systems can estimate the optimal cleaning length and frequency based on the dust pattern. The optimal cleaning duration and frequency can thus be determined. More research is required in this area, particularly in the GCC, where the situation is extremely dire.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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