Effects of different environmental and operational factors on the PV performance: A comprehensive review

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Abstract

Conventional fossil fuel-based power generation is one of the main contributors to global environmental pollutions. The rapid depletion of fossil fuel reserves as well as their adverse environmental impact heighten the quest for cleaner and sustainable energy resources to generate electricity. Solar energy is an unlimited and immeasurable source of renewable energy that is used for direct electricity production through the solar PV cell. However, environmental conditions as well as operation and maintenance of the solar PV cell affect the optimum output and substantially impact the energy conversion efficiency, productivity and lifetime, thus affect the economy of power generation. In this study, an investigation about recent works regarding the effect of environmental and operational factors on the performance of solar PV cell is presented. It is found that dust allocation and soiling effect are crucial, along with the humidity and temperature that largely affect the performance of PV module. Additionally, the wind itself carries a significant amount of dust and sand particles, especially in the deserted areas. Deposition of dust in humid conditions forms adhesive, sticky mud on the PV cell and worsens the situation as it reduces the power generation up to 60–70%. This study discusses advanced approaches to mitigate the effects of these factors with their relative merits and challenges. Finally, a guideline is proposed to minimize the effect of different environmental and operational factors to optimize the performance of solar PV cell.

1 INTRODUCTION

Currently, conventional fossil fuels such as oil, coal and natural gas are extensively used as the primary energy source. However, they are limited in supply and have an environmental risk associated with extracting, transporting and utilizing them. Approximately 66% of the global carbon dioxide and other greenhouse gases (GHG) emissions are generated from fossil sources.1 In contrast, renewable energy, especially solar, is available everywhere, is non-pollutant and has minimal impact on the environment, making it most suitable for the sustainable energy source. The International Energy Agency (IEA) reported that solar photovoltaic (PV) could provide 11% of the total green energy worldwide, which is equivalent to a substantial of 2.3 Gigatonnes CO2 reduction emission every year.2

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The sun is the source of solar energy and delivers 1367 W/m² solar energy in the atmosphere. The total global absorption of solar energy is nearly $1.8 \times 10^{11}$ MW, which is enough to meet the current power demands of the world. Figure 1 illustrates that the solar energy generation capacity is increasing significantly in the last decade, and further extrapolation demonstrates that its future capacity could increase up to 1700 GW by 2030.

Although solar PV could be a sustainable alternative to fossil sources, they still have to deal with the issue of poor efficiency. Although it is theoretically possible to get the highest efficiency of 29% in commercial PV, this value only reaches a maximum of 26% in the actual case. Various external and internal factors are responsible for the degradation of PV panel efficiency (Figure 2), namely environmental, constructional, installation and operation and maintenance. Although the PV constructional factors and their installation processes are upgraded gradually, there is still a tremendous challenge to deal with the environmental factors.

PV module can effectively receive solar radiation intensity and spectrum. However, dust, snow or any other natural or artificial shadowing can reduce the amount of solar irradiation received by the module. In addition, dust and air pollutants are absorbed by humid air, resulting in soiling on the module-reduced irradiance, which causes low PV power generation. PV panel heats up because of the direct exposure to the sun. The amount of light absorbed by the module’s parts other than the solar cells contributes to the module’s heating which leads to a decreased band-gap energy, resulting in a poor power output. Solar panels are mounted in certain height to vent off the excess heat energy. The PV module output power can be increased by adding ventilation, fans or cooling systems to assist the movement of air around the panels. Naturally, areas with high wind flow rates can be benefitted from forced convection heat transfer in PV module cooling. Though the wind cools the PV panel, it also carries dust and sand particles with it, which reduces PV power output. Therefore, some operational and maintenance works are required to mitigate the negative environmental effect in some cases. As a result, a detailed analysis is required by incorporating all the environmental, operational and maintenance factors and their corresponding effect to reduce PV performance.

Many research works have already been published to address different factors that impact the performance of solar PV panel. For example an extensive review works on dust deposition and cleaning the methods are carried out by Kazem et al. They reported that the desert areas face significant power losses (up to 80%) due to dust accumulation. In another work, Chanchangi et al. reported a literature review on the effects of dust on PV module performance in Nigerian climatic condition and the potential measures to mitigate them. The impact of air pollution and soiling on the performance of PV module and its techno-economic performances is comprehensively reviewed by Song et al. However, these review works mainly focus on the dust accumulation and their mitigation techniques. Present study goes further by reviewing the operational and maintenance factors that affect the performance of PV module along with different environmental factors including dust and soiling. Research works on different environmental, PV systems installation, cost and other miscellaneous factors on the PV performance are reviewed by Fouad et al. Although environmental factors, installations and other miscellaneous factors are extensively reviewed in their study, the operational and maintenance factors are not studied.

Although individual factors are extensively reported by many researchers, the review works on different environmental, operational and maintenance factors on the performance of PV module are rarely investigated. In the present study, a comprehensive review of the different environmental, operational and maintenance factors affecting the performance of the solar PV modules is performed. The study also identifies the advanced measures to reduce the effects of the factors liable for the degradation of productivity of the solar PV. The review paper could assist...
the investigators and policymakers to realize the different solar PV factors to improve the power output and make it economically feasible.

2 \hspace{0.3cm} \textbf{ENVIRONMENTAL FACTORS}

The PV modules have to be exposed to the atmosphere under direct sunlight. Therefore, the performance and efficiency of the PV module are heavily influenced by environmental factors such as irradiance, temperature, dust allocation, soiling, wind, shading, humidity etc. The following sections describe the impacts of these factors.

2.1 \hspace{0.3cm} \textbf{Effects of solar irradiance}

Irradiance is the energy that strikes a unit horizontal area per unit wavelength interval per unit time.\textsuperscript{13} The PV panel output significantly depends on solar power or solar irradiance as the solar resource is highly variable.\textsuperscript{14} The degree of variability depends on the time resolution at the sub-second level and rises with the increase in time resolution.\textsuperscript{15} Irradiance usually varies due to the weather, seasonal changes, geographical location, time of the day and sun position in the sky.\textsuperscript{16} According to the changes in sun altitude, the sun’s location changes throughout the day.\textsuperscript{12} Cloudy condition is primarily

\begin{figure}
\centering
\includegraphics[width=	extwidth]{fig2.png}
\caption{PV panel efficiency degradation factors}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=	extwidth]{fig3.png}
\caption{Irradiance value changes with different cloudy conditions\textsuperscript{17}}
\end{figure}
responsible for variable irradiance value, as reported in Figure 3.

The PV modules receive both direct light from the sun and scattered light from the sky, ground and nearby objects. However, the significant contribution comes from direct solar irradiation. The estimation of incident irradiance becomes complicated when nearby objects create shadows or reflect sunlight onto the PV modules. The solar panel would be tilted, facing the sun to receive the maximum amount of irradiance. The optimum tilt angle is a function of the latitude angle ($\phi$) of the location. The tilt angle deviates $-15^\circ$ from the latitude angle in summer and about $+15^\circ$ from the latitude angle in winter. Many solar tracking mechanisms are used to align PV panels with the direct component of solar irradiance. Each degree of deviation from the south in the azimuth orientation causes a 0.08% irradiance loss.

The output of the PV module increases as the irradiance increases. The PV module can measure the irradiance based on the G-P (sun radiation-output maximum power) curve, as it is approximately linear. Therefore, based on the literature, the effect of solar irradiance on the performance of the PV panel cannot be computed by a particular percentage due to the linear relationship between the module current and the irradiance value.

2.2 Effects of temperature

The efficient production of electricity strongly depends on the module temperature of a PV panel. As the module temperature increases, electrical efficiency decreases since the PV modules convert only 20% solar energy into electricity and 80% into heat. There is a strong relationship between module temperature and the bandgap energy of the PV cell material. Bandgap energy generally reduces at high operating temperature conditions. It influences the cell to absorb longer wavelength photons and typically increases the lifetime of the minority carriers. However, these factors slightly increase the light-generated current ($I_{sc}$) that leads to a drop in the open-circuit voltage ($V_{oc}$), resulting in an overall reduction of the cell fill factor (FF).

Fill factor measures how much series and shunt resistance are present in a solar cell and its circuit. Electricity generation in the PV module depends upon short circuit current ($I_{sc}$), and the open-circuit voltage ($V_{oc}$), as the maximum power and is given by Equation (1):

$$P = V_{m} \times I_{m} = (FF) \times V_{oc} \times I_{sc}$$ (1)

Based on the literature, module temperature is a function of environmental factors such as solar irradiance, wind speed, ambient temperature, as well as some PV constructional factors such as materials and glass transmittance. The module temperature can be calculated using Equation (2):

$$T_{mod} = T_{amb} + \text{Irradiance} \times \exp (-a - b \times WS) + \Delta T \times \frac{\text{Irradiance}}{1000}$$ (2)

where $a$, $b$ and $\Delta T$ are the constants, and for glass/cell/polymer sheet, the values are 3.56, 0.0750 and 3 respectively. In addition, WS refers to the wind speed (m/s). From the literature, it is found that the efficiency of a solar cell slightly increases to 12% with a cell temperature of 36°C, beyond which efficiency falls with increasing temperature shown in Figure 4.

The solar cell efficiency of single crystal silicon greatly depends on the cell operating temperature. At an operating temperature of 56°C, the efficiency of the solar cell is decreased by 3.13% at 1000 W/m² irradiation level without cooling. Studies also show that the efficiency is reduced by 69% at 64°C. Furthermore, efficiency drops to 5% when the module temperature increases from 43 to 47°C, indicating the effect of wind speed on the rate...
of temperature increase. Without cooling, electrical efficiency decreases by 0.03%–0.05% for every 1°C increase in solar cell temperature. The thermal dissipation and absorption properties of the encapsulating or cover materials influence the PV performance. Research is currently going on to enhance power extraction from PV by cooling techniques. Table 1 represents how several cooling methods compare. The Section 3.3 on cooling techniques goes into great detail. Due to the increasing cost and efficiency, Verma et al. showed that single cooling technology is insufficient to develop for large solar PV projects. In contrast, heat transfer and overall efficiency will improve if both phase change material (PCM) and microchannel water cooling are used together.

### 2.3 Effects of dust accumulation

The efficiency of PV modules is degraded when the dust, water vapour, air molecules and other pollutants in the atmosphere prevent sunlight from falling on the PV panel. Sunlight can be scattered by the dust particles in the air, which are larger than the incoming solar beam wavelength and result in reduced solar irradiation. Dust can also form a thick layer on the PV module surface. Dust layer can change the optical properties to promote light reflection, absorption and reduce surface transmissibility, hence PV module output. Dust accumulation depends on environmental factors such as wind velocity, humidity, rainfall, source of dust particles, particle type, PV module technology and PV module surface cover. It becomes more severe in desert areas where dust density is high and suffers from less rainfall. Studies in Saudi Arabia show that the average degradation rate of the efficiency is 6–7% per month that might increase to 13% in six weeks without cleaning.

Additionally, output power generation could drop to half of its maximum value (50%) without cleaning. Elminir et al. have shown that the output power is decreased by about 17.4% per month in Egypt. The condition becomes more unpleasant with air pollutants, toxic gases, suspended particles, and dust that causes over 60% reduction in PV energy output. Dust particles settle on module cover because of the gravity force. These particles absorb water vapour in humid air environments and form adhesive and sticky mud at the surfaces. Said et al. have shown that a dust accumulation period of 45 days reduces overall glass cover transmissance by 20%. The impact of rain on dust deposition is evident. When the annual rainfall in Egypt is 18–50 mm, PV power output drops to 60–70%. However, studies in the UAE and Qatar, which receive an annual rainfall of 80–90 mm and 70–75 mm, have demonstrated a lower (10%) deterioration of PV power generation than Egypt. Moreover, the conversion efficiency is reduced with increasing dust density, as shown in Figure 5. In some regions, dust density may drop due to rainfall, wind and other environmental parameters. The reduction of PV efficiency for dust accumulation in different climatic regions is enlisted in Table 2. An appropriate cleaning cycle can retrieve maximum PV module output throughout the year.

### 2.4 Effects of soiling

Dust accumulation can also cause soiling on the PV module. In humid environments, the dust particles are settled at PV surfaces and adsorb water from the air to develop mud. The atmospheric humidity highly influences the adhesive force between dust particles and PV surfaces. Therefore, an increase in absolute humidity increases dust accumulation. Moreover, vapour condensation on the PV module forms capillary bridges in gaps between the particles and the surface. It generates large meniscus forces that enhance the particle and surface adhesion, which helps dust build-up. Soiling causes both soft and hard shading on the PV panel and reduces the power output. Smog in the atmosphere is responsible for soft shading, and soil mass or mud on the panel causes hard shading. Although hard shading on some cells of a PV module causes a decrease in module voltage, the current remains constant since the unshaded cells still receive solar irradiance. Similar to dust accumulation, PV power loss due to soiling varies by geographical location because different dust has different effects on light transmission. The relation between soil mass and PV power loss has been studied well in the literature.

In some cases, PV power loss is linearly proportional to soiling mass. The surface is heavily soiled by an increase in soil mass, when new dust particles may settle on existing particles, it does not cause further obstruction of light. Studies show that transmittance reduces by 30% for coated glass and 37% for uncoated glass after 40 days of exposure in Saudi Arabia. Transmission reduction varies with glass materials; for example multilayer (ML) (0.85%), self-cleaning (SC) (1.30%), anti-reflection (AR) (1.75%) and regular glass (2.63%) as tested in Belgium with 35° tilt angle and periods of average rainfall. Figure 6 represents the effect of soiling at different PV tilt angles. It shows that the soiling impact is more concerning for the flatter panel orientation or lower tilt angle. Modifying the surface texture and surface energy improves the hydrophobicity, which minimizes the dust settling at the panel surface and enhancing the transmittance. Natural cleaning by rainfall and additional mechanical cleaning by fluids or water can solve this soiling issue.
| Cooling techniques               | Conditions                                      | Achieved PV panel temperature range | Energy increases                                             | References |
|---------------------------------|------------------------------------------------|-------------------------------------|-------------------------------------------------------------|------------|
| Natural ventilation             |                                                 | Reduced to 55.5°C from 76.7°C       | Annual electrical energy increased by 2.5%                  | 30         |
| Active ventilation              | Forced convection with an airspeed of about 2 m/s | Reduction of cell operating         | Electrical output increased by 8%                           | 31         |
|                                 |                                                 | temperatures of 18 K                |                                                             |            |
| Active cooling by water         | Water sprinkle on both sides of PV panel        | 30°C module temperature reduction   | 7.7% and 5.9% increase in electric power output and         | 32         |
|                                 | simultaneously                                   |                                     | efficiency respectively                                    |            |
| Active cooling by water         | Water film cooling on the front surface of the  | 26°C module temperature reduction   | 15% increase in power output                               | 33         |
|                                 | panel                                          |                                     |                                                             |            |
| Active cooling by water         | Direct water spraying                            | 23°C module temperature reduction   | Increases the mean PV cell efficiency, subsystem            | 34         |
|                                 |                                                 |                                     | efficiency and total efficiency by 3.26%, 1.40% and         |            |
|                                 |                                                 |                                     | 1.35% respectively                                         |            |
| Natural vaporization cooling    | Installation of panels on the river canals and  | 39.3–48.3°C                        | 7.3% increase in power output                               | 35         |
|                                 | other places where vaporization exists          |                                     |                                                             |            |
| Liquid immersion cooling        | A 250X dish concentrator with 940 W/m² direct  | Can be cooled to 45°C               | Electrical performance degrades after a fairly              | 36         |
|                                 | normal irradiance                               |                                     | long time immersion in the de-ionized water                |            |
| Diffusion of water by cotton wicks on PV panel backside | Standalone flat PV modules | 20°C decrease in module temperature and cool down to 45°C | 15.5% increase in electrical efficiency | 37         |
| Thermoelectric cooling         | A thermodic cooling module is considered to be  | 344.41 K (when the ambient          | 0.0704 W extra power output                                 | 38         |
|                                 | attached to the backside of a single PV cell    | temperature is 350.45 K)            |                                                             |            |
| Thermoelectric cooling         | Solar insolation range of 0.8–1 kW/m²           | Cell temperature 25–45°C            | Increases efficiency in the range of 1–18%                  | 39         |
| Thermoelectric cooling         | Using Peltier effect                             | Reduces the operating temperature   | Increases the panel efficiency up to 1.3%                   | 40         |
|                                 |                                                 | from 83°C to 65°C                  |                                                             |            |
| Water cooling                   | 2 L/min water through twelve nozzles            | Up to 22°C                         | Net electricity gain increased by 8–9%                     | 41         |
| Radiation and free convection  | An open channel is fitted beneath the PV module  | 10–20°C reduction in module        | 1–2% gain in efficiency                                   | 42         |
|                                 |                                                 | temperature                         |                                                             |            |
| Extended areas                  | Using lapping fins                              | Lower the module temperature by     | Panel efficiency is 10.68%                                  | 43         |
|                                 |                                                 | 24.6°C                              |                                                             |            |
| PVT system                      | Using CuO nanofluid                              | Surface temperature drops up to     | Maximum power reaches up to 51.1% than no cooling system   | 44         |
|                                 |                                                 | 57.25%                              |                                                             |            |
| Heat pipe technology            | Pulsating heat pipe cooling system              | 5°C cell temperature reduction      | Increasing in electrical efficiency of 0.77%                | 45         |
| Latent heat sink by PCM         | Using CaCl₂·6H₂O                                 | 25–30°C                            | Power saving of 13%                                        | 46         |
| Latent heat sink by PCM         | Two types of PCM are used                       | 42°C                               | -                                                           | 47         |
| Latent heat sink by PCM         | PCM container is attached to the backside of    | 12°C reduction in module temperature| 0.4 V gain in voltage                                       | 48         |
|                                 | three 65 W panel                                |                                     |                                                             |            |
2.5 | Effects of wind velocity

Wind conditions, including wind speed and direction, control the energy produced by a photovoltaic module.26 The impact of wind on PV performance is described by factors such as module temperature, surface structure and dust deposition.27 Section 2.2 explains the way of enhancing PV module efficiency by decreasing the module temperature. The most cost-effective option for cooling is using convective heat transfer by natural wind flow to the highest possible extent.85 The rise in temperature of PV cells is extremely sensitive to wind speed rather than wind direction.86 Surface shape and structure has a clear impact on convection cooling of PV panel. Structured and grooved glass cover surfaces may operate at low temperatures at higher wind speeds. However, the cooling effect is significantly higher for the flat surface at low wind speed.87 Studies in the USA87 have shown that for 10 m/s wind speed, the operating temperature can be lowered by 3.5°C with a grooved glass cover.

Furthermore, the temperature can be decreased up to 10°C for 2.8–5.3 m/s wind speed for KSA86 and half of its operating temperature at 12 m/s in Slovenia.88 Additionally, the wind blows away dust particles from the PV module surface and reduces dust deposition.89 For example a study in Egypt shows a decrease in dust deposition from the module at a particular tilt angle due to blowing wind.62 However, it negatively impacts the desert area, where wind itself carries a significant amount of dust and sand particles.90 In Libya, dust deposits over the PV surface rapidly at a high rate due to atmospheric wind circulation.91

2.6 | Effects of shading

Shading is the obstruction in the path of light falling on the PV panel. The shadowing effect lowered the PV power output.92 Shading can be of various types, like hard shading, soft shading, self-shading etc.93 Hard shading occurs due to the accumulation of dust, snow, bird droppings, leaves etc. Additionally, poles, trees and buildings block the sunlight in a clear and definable shape.94

On the other hand, atmospheric dust, fog and smoke reduce irradiance intensity and create a soft shading on the PV module.79 The preceding row of PV modules causes self-shading (Figure 7). Some studies have developed several techniques to minimize the effect of self-shading. Brec79 has developed an empirical formula with 30° inclination angle to calculate relative annual energy losses (RAEL) due to self-shading, which is estimated by Equation (3), where $A$ is an energy loss parameter, and $F$ is the spacing factor $= d/b$ ($1.5 < F < 5$).

\[
RAEL = A \times e^{-2.3F - 0.001 \times F + 0.01}
\] (3)

Partial or complete shading depends on module position, array configuration and shading scenario and significantly decreases PV module output.96 Partial shading blocks some cells of a PV module and severely affects module output because the shaded cells cannot produce any current. Therefore, the current produced in non-shaded cells flows through the shaded cells causes its operation in a negative voltage region and dissipates power rather than generate.97 Moreover, the maximum power point tracker (MPPT) under shading may shift from global maximum power point (MPP), thus producing less energy.98 Many researchers have investigated the losses and developed technical solutions to reduce the losses caused by complete or partial shading.97,98 Shading effects on the PV power output are estimated using different numerical and experimental configurations, and some of them are presented in Table 3.
2.7 | **Effects of humidity**

The relative humidity is an influencing factor that is responsible for the accumulation of tiny water droplets and water vapour on solar panels from the atmosphere. Water droplets can refract, reflect or diffract sunlight away from solar cells and reduces the number of direct components of solar radiation hitting them to produce electricity. Additionally, the radiation intensity varies non-linearly with humidity because of greater scattering angles with smaller water vapour particles. Long-term exposure in a humid atmosphere corrodes the PV modules due to the moisture ingress to the solar cell. In addition, the moisture retention in the module housing increases the electrical conductivity of the material and leakage currents.

Moreover, water condensation at the interface between the encapsulant and the solar cell materials creates increased corrosion rates that risk encapsulant delamination. Degradation in the module performance can be overcome either by using a proper hermetic seal or an encapsulant loaded with desiccant with a very low diffusivity. In addition, the high relative humidity (RH) creates the formation of sticky and cementing dust layers on PV surfaces that may cause soiling and results in a low power output. The efficiency of solar cells increases from 9.7% to 12.04% when relative humidity is decreased from 60% to 48%. In terms of power, an increase in relative humidity by 20% reduces the power generation by 3.16 W. Another study shows that PV power output decreases by 40% at a relative humidity of 76.3% during the rainy period and decreases by 45% at 60.5% relative humidity in the cloudy condition. Although reducing irradiance due to moisture is a natural loss, dust adhesion loss on the module surface may be recovered by proper cleaning methods.

### 3 | **OPERATION AND MAINTENANCE FACTORS**

The photovoltaic module is degraded over time. However, some operational and maintenance factors can reduce the degradation of PV modules and make them economically convenient. The following section discusses some of these factors.

#### 3.1 | **Panel degradation**

The gradual deterioration of the characteristics of the PV system is termed panel degradation and may affect its
ability to generate power. As manufacturer suggestions, a panel is degraded when its power reaches below 80% of its initial power.\textsuperscript{111} Several factors such as temperature, humidity, irradiation, mechanical shock are responsible for the deterioration of PV panels.\textsuperscript{111,112} Table 4 presents different reasons for panel degradation. Additionally, hot-spot formation is a concerning issue since high temperatures could damage a cell.\textsuperscript{113} Partially shaded, damaged or mismatched series-connected cells produce hotspot heating. Studies showed some algorithms to mitigate hotspots. Jerada et al.\textsuperscript{114} proposed an accurate and fast-tracking response of hotspot detection. Proper maintenance of all these issues can remove the unwanted power generation losses.

3.2 | Cleaning methods

The effects of dust collection and soiling on glass transmittance and overall PV power generation have already been discussed in Sections 2.3 and 2.4. Studies show that the appropriate cleaning system and regular cleaning can improve its efficiency. The study also suggested that the cleaning frequency of approximately 20 days when the PV module is exposed to desert conditions.\textsuperscript{115} The most prominent pollutants deposited on the PV are particulate matter (PM) from fossil fuel combustion.\textsuperscript{116} Researchers investigated the cleaning process, cleaning agent and damage effect. However, the best and most appropriate cleaning method should be designed based on the model pattern, PV capacity and power generation. The summary of the cleaning techniques is reported in Table 5.

3.2.1 | Natural cleaning

PV panels are mostly cleaned by rain and wind in the natural PV cleaning technique. In order to facilitate the natural cleaning, panels are normally set at a tilt angle to wash away the dust particle by rainwater falling on the panel’s surface. However, this procedure typically leaves behind dust that has been attached to the panels as a result of wetness, and it takes a lot of rain to remove it. When there is heavy soiling and insufficient rainfall, the reliability of such a technique to wash off the deposited soil is disputed. It is reported that the dust build-up, may result in daily PV performance losses of more than 20% in dry seasons when the rain is discontinued.\textsuperscript{117} Paudyal et al.\textsuperscript{118} examined the effect of dust accumulation on PV module and the seasonal rainfall in Kathmandu. To evaluate the impact of utilizing natural cleaning of PV module by air movement at a speed of 0.23–57.56 m/s, Jiang et al.\textsuperscript{119} simulated the suspension of dust particles with sizes ranging from 0.1 to 100 mm and discovered that dust particles larger than 1 μm in diameter are easily dispersed by wind.

3.2.2 | Water cleaning

This approach necessitates a significant amount of water under constant high pressure, to fend off any soiling PM adhered on the PV panel surface. The pressurized water is occasionally blended with a particular cleaning solution to wash away the dust particle, and it can also be used
to cool down PV panels in semi-arid and desert areas. The surface temperature of the headboard was reduced by 45.5%, while the temperature of the back surface was reduced by 39%, according to the results of the experimental investigation by spraying water. The efficiency of the cleaned and cooled panel was 11.7% over the trial period, compared to 9% for the non-cleaned and non-cooled panel.121 According to the findings from a study in Egypt, the PV efficiency dropped by 50% after 45 days using the natural water flow.120

### 3.2.3 Manual cleaning

In manual cleaning technique, dust particles are cleaned with special brushes with bristles to avoid scratches on the surface of PV module. It is much more effective than rain cleaning in restoring the solar panel surface to its original state. Shehri et al.123 performed an empirical research to identify the most effective usage of nylon, cloth and silicone rubber foam brushes for cleaning to enhance PV efficiency. Mart et al.122 showed that pure water does not form a residue on the PV surface. Therefore, pure water acts as the best cleaning agent rather than other chemically active materials such as detergent, network water and liquid soap. The authors recommended different cleaning tools such as glass razor, squeegee, chamois, velour and sponge based on the experimental result. The squeegee causes maximum scratch and decreases energy, exergy and power conversion efficiency by 17.87%, 19.37% and 19.62% respectively.122

### 3.2.4 Mechanical cleaning

Cleaning with a mechanical and automatic water system is more efficient than cleaning with natural rain and
## TABLE 5 Summary of important PV module cleaning techniques

| Cleaning techniques | Study area | Conditions | Performance evaluation | References |
|---------------------|------------|------------|------------------------|------------|
| Self-cleaning material | - | TiO₂ coating on glass cover | Make the surface super hydrophilic and self-cleaning | 9 |
| Natural cleaning | Spain | With rain water and wind | Increase output more than 20% | 117 |
| Natural cleaning | Nepal | Without cleaning for 150 days | Efficiency dropped by 29.76% | 118 |
| Wind cleaning | - | Effects of adhesion force, hydrodynamic force and torque for rolling detachment mode are analysed | Wind velocity can remove particles with diameters ranging from 0.1 µm to 100 µm | 119 |
| Water cleaning | Egypt | Without cleaning of 45 days | Efficiency dropped by 50% | 120 |
| Water cleaning | Egypt | Cleaning and cooling at the same time | Efficiency improved by 2.7% | 121 |
| Manual cleaning | Turkey | Pure water with cleaning tool and cleaning agent | Increase efficiency | 122 |
| Manual cleaning | Saudi Arabia | For cleaning, a variety of materials are available such as nylon, cloth and silicone rubber foam | Enhancement in the maximum power output of solar panels cleaned with silicone rubber is around 1% | 123 |
| Mechanical cleaning | - | Robotic water spray | Increases the PV module efficiency by 15% | 67, 124 |
| Mechanical cleaning | - | Required a high-voltage supply | Removes over 90% of dust in less than two minutes | 125 |
| Electro Dynamic Screens (EDS) | USA | Cleaning efficiency up to 90% | Increase efficiency by 32–73% | 126 |
| Forced air flow cleaning | UAE | Used air coming from air-conditioning fans | Annual power generation increases by up to 17% | 127 |
| EDS, air-blowing and nanocoatings | Saudi Arabia | Required high-voltage supply/solar panels are coated with super-hydrophobic thin films. | Automatic cleaning offers the highest income for high dust accumulation and manual cleaning provides the highest income for low soiling | 128 |
| Automatic, semi-automatic and manual cleaning technologies | - | Optimal cleaning strategy is estimated | Panel surface stability against the impact of water drops, strong acid and strong alkali | 129 |
| Self-cleaning material | China | Super hydrophobic surface coating with highly antireflective properties are over glass covers of solar cells | Coating shows no reduction of PV performance after 4000 h of exposure | 130 |
| Hydrophobic anti-soiling coating | UK | Hydrophobic coatings deposited (1 mm thick) on glass surfaces | | 131 |
air. According to a study, a robotic water spray cleans and cools the PV panel that increases the PV module efficiency by 15%. In dry times, Mani et al. recommended cleaning the panel once a week and daily when dust collection is high. The cooling technique employed by their study includes automation, with the system being controlled by a microcontroller and sensors. In this case, although it consumes extra amount of electricity for its functioning, it is a labour-saving method for cleaning panel surfaces.

3.2.5 | Electro-dynamic screens (EDS)

An electro-dynamic screen (EDS) mounted on a solar PV panel can ensure automatic and continuous clearance of accumulated dry dust. A high-voltage supply is used to create an electric field of a transparent screen, which assists in the removal of charged and uncharged dust particle from the PV panels by moving them over the panel’s edge. This cleaning technique is helpful in dry, arid and desert areas and removes over 90% of dust in less than two minutes. In order to produce the electric field, the system requires a high-voltage supply, which lowers the generating efficiency by 15%. This technique has been found to be ineffective in eliminating moist dust particles or those of cement origin, and its effectiveness is restricted to the condition of micro and tiny particles, according to studies. In dry regions, this method is used to improve the PV’s lifespan and minimize the damage caused by UV irradiation by replacing screens with polymer or weather-resistant glass.

3.2.6 | Forced air-flow cleaning

Assi et al. used air coming from air-conditioning fans to flow directly on the solar panels, removing the dust forcefully in the UAE climatic condition. Alqatari et al. created a model to investigate three dust removal methods such as EDS, highly hydrophobic nanocoatings and air-blowing mechanisms on the output of PV module in six different areas in Saudi Arabia. Tanesab et al. examined a self-cleaning solar system using air blower in the UAE.

3.2.7 | Self-cleaning material

Water-repelling (hydrophobic) or water-dispersing (hydrophilic) qualities enable self-cleaning of the surface of PV module. When a waterfall falls on a hydrophobic surface, it readily flows away and swept away the dirt sticks to the surface, resulting in a clean surface. The idea behind this technique is to cover the PV surface with a hydrophobic coating and a thin layer that acts as a barrier, preventing water from adhering to the surface. As water travels over the surface and takes up the dirt, it is also known as ‘active cleaning’. The nanofilm made of TiO₂, is used chemically, and added to the PV surface to form a super hydrophilic surface. TiO₂ is extensively used in the coatings on the cover glass surface to provide self-cleaning surfaces. Additionally, SiO₂ and ZnO, ZrO₂ and Si₃N₄ can be used as a substitute for TiO₂.

3.3 | Cooling methods

The performance of PV cells decreases with the increase in operating temperature because of increasing internal carrier recombination rates caused by increased carrier concentrations. This intrinsic carrier concentration depends on the bandgap energy, where lower bandgap gives higher intrinsic carrier concentration. The increase in solar cell temperature reduces the bandgap since the energy of electrons increases in the cell material. The PV power out and overall efficiency both linearly depend on the operating temperature. The operating temperature of PV module is influenced by sunlight intensity, dust accumulation, wind direction, humidity etc. Nature controls these parameters, and some of the factors are beyond research capabilities in an open environment. However, there are reliable and cost-effective alternative methods to control the operating temperature. Among them, cooling methods are most economical and consistent to limit the temperature rise. The cooling techniques to reduce the operating temperature of PV modules are essential in maintaining optimum power output. Both active and passive cooling techniques could be used to cool the PV modules. Active cooling needs liquid or gas and mechanical work such as fans to force air and pumps to circulate water to extract excess heat from the PV module. In contrast, passive cooling utilizes either the high thermal conductivity of metals or extruded surfaces to enhance the convective heat transfer to the atmosphere. The most common cooling methods include but are not limited to:

3.3.1 | Direct spraying

Water is an excellent coolant and could be directly sprayed through the sprinklers on the PV modules with a water pump to cool the surface temperature. Abdolzadeh and Ameri experimentally showed that direct water spraying increases the mean PV cell efficiency, subsystem efficiency and total efficiency by 3.26%, 1.40% and 1.35% respectively.
respectively. In similar research, Dwivedi et al.\textsuperscript{139} found that water spraying is cost-effective, and the electrical efficiency of PV module can increase up to 15% by direct spraying even in extreme weather. Nizetic et al.\textsuperscript{32} applied this water spraying technique in Mediterranean climatic conditions, and experimental investigations showed a maximum increase of 16.3% in electric power output and 14.1% increase in PV panel electrical efficiency. Bevilacqua et al.\textsuperscript{140} compared different cooling methods and reported that spray cooling is the most effective technique with the efficiency reached up to 14.3% compared to the 12.7% of the reference module.

3.3.2 | Increasing the surface area (fin/extended areas)

Fins are the extended area that absorbs heat from the PV module by thermal contact and dissipates the heat to the surrounding medium either by direct or radiant contact. The working medium could be ambient air, induced air draft or coolant liquids. They are made of very high thermal conducting materials such as copper and aluminium alloy. Although the fin surfaces need to be flat and smooth to reduce resistance, they could have different shapes such as transverse ribs, V-shaped ribs and arc-shaped to enhance the heat transfer coefficient. Elbreki et al.\textsuperscript{43} applied a passive cooling method using fins and planar reflector to reduce the module temperature. Their study suggested that the cooling with lapping fins provides the best performance by lowering the module temperature by 24.6°C compared to the reference level while maintaining a panel efficiency of 10.68%. Amr et al.\textsuperscript{141} used fin in passive cooling technique to enhance the PV performance. The study reported that the fin reduces the cell temperature by 4–5°C and significantly increase the panel efficiency. Bayrak\textsuperscript{142} used ten different fin configurations in a natural cooling system to investigate the performance of a PV panel in Turkey's climatic regions. Results reported that the best performance is obtained for staggered-vertical fin with energy and exergy efficiencies are estimated as 11.55% and 10.91% respectively.

3.3.3 | Combined with a thermal system (PVT)

The solar PV combined with a thermal system can be used to reduce cell temperature. Rostami et al.\textsuperscript{44} used CuO nanofluid in a PVT system to increase the efficiency and cooling performance of a PV module. The researchers reported that the average surface temperature drops up to 57.25%, and maximum power reaches 51.1% compared to no cooling system. Kasaeian et al.\textsuperscript{143} used a modified air-cooled PVT system to increase the PV performance by forced convection techniques and found that the thermal efficiency of the system is in the ranges of 15–31%, while the electrical efficiency is in the range of 12–12.4%. Tarabsheh et al.\textsuperscript{144} experimentally investigated the water-based cooling in the PVT system to enhance the electrical efficiency of the PV modules.

3.3.4 | Heat pipe technologies

The heat pipe absorbs the heat from the PV module, reduces cell temperature and improves electrical efficiency. Alizadeh et al.\textsuperscript{145} numerically investigated the efficiency PV module using a closed-loop pulsating heat pipe. Authors reported that the use of heat pipes in passive and active cooling increase the improvement rate by 23% and 35% respectively. Tang et al.\textsuperscript{146} used a novel micro heat pipe array to cool the solar panel by air and water cooling and found the power output is increased by 8.4% for air cooling system and 13.9% for water cooling system. Roslan and Hassim\textsuperscript{45} used pulsating heat pipe cooling system to improve the PV performance. The study reported that a reduction of 5°C cell temperature and the rise of electrical efficiency of 0.77% can be achieved.

3.3.5 | Phase change materials

Phase change materials are a latent heat storage material, and it can absorb excess heat from the PV panel by using its latent heat while maintaining a constant temperature for a certain period. Therefore, incorporating PCM with the PV module reduces the operating temperature and provides higher electrical efficiency. Choubineh et al.\textsuperscript{147} used salt hydrate as PCM in an air-cooled PV module to improve panel performance. Their study found that the salt hydrate PCM reduces the panel temperature by 3.7–4.3°C and thus, improves the electrical efficiency by 9%. Hachem et al.\textsuperscript{148} found that the pure PCM increases the efficiency by 3%, while combined PCM raises the efficiency up to 5.8%. Hasan et al.\textsuperscript{46} also studied a PV-PCM system using two different PCM (capric-palmitic acid and CaCl$_2$·6H$_2$O) materials to reduce heat-related PV losses and reported that both PCM materials achieved higher PV temperature drops up to 21°C, resulting in a 13% power savings.

3.3.6 | Thermoelectric cooling (TEC)

Thermoelectric cooling is an advanced technique that uses n-type and p-type semiconductors, connected in
series electrically and in parallel thermally. The thermoelectric devices operate based on the Peltier effect, which creates a temperature gradient by transferring heat between two electrical junctions. When a voltage is applied across the junction, it forces an electric current to flow. Therefore, heat is removed from one junction to another and cooling occurs. Benghanem et al. investigated the performance of solar cells by using a thermoelectric cooling system. Their study reported that the thermoelectric module reduces the operating temperature from 83°C to only 65°C and increases the panel efficiency up to 1.33% after cooling but increases the total cost by 6%. Kane et al. designed an active cooling method for PV panel using thermoelectric devices at the backside of the module and found that the integration of thermoelectric device into PV module can increase electrical efficiency in the range of 1–18% for solar insolation 0.8–1 kW/m² while reducing the operating temperature by 6–26%.

3.4 Battery maintenance

Batteries are used in the solar PV system to store excess electrical energy generated by the PV cell and to supply this energy when the sunlight is not available. Additionally, battery helps to supply stable electrical power against fluctuating characteristics of the PV system output. Lead-acid batteries offer the best balance of capacity per cost, and it is a common battery used in stand-alone power systems. The water level in each cell of a battery is essential for proper charging and discharging cycle. Therefore, keeping the water level at a safe level may require watering the battery regularly. However, overwatering and underwatering can both degrade the battery life. In addition, batteries are discharged and recharged periodically, and during charging time, the battery will consume some of the water. Therefore, the liquid levels in the cells must be checked, and water should be added to depleted cells if required based on the manufacturer’s specifications. According to Quansah et al., reported that PV degradation rate of 1.3%/yr and 0.8%/yr when battery are charged incorporated with PV modules. In another study, Rajput et al. found that PV faces a degradation rate of 1.9%/yr when an old battery-charging method is installed with it. Ideally, a battery bank should be sized to be able to store power for 5 days of autonomy during cloudy weather. If the battery bank is smaller than 3 day capacity, it is going to cycle deeply on a regular basis, and the battery will have a shorter life. Batteries must be located in an area without extreme temperatures and with adequate ventilation when they are used in a PV system.

4 CONCLUSIONS

The integration of solar PV into the existing grid network and stand-alone application has increased significantly in recent years. However, the performance indicator of the PV panel is affected mainly by climatic conditions and weather parameters. This article has effectively identified the different factors affecting the power output of a PV module. Current study has also identified the advanced measures to mitigate the effects of the various factors responsible for the degradation of solar PV performance. Findings and recommendations from the study can be outlined as follows:

- PV output significantly depends on available solar energy falling directly on the module, and 0.08% loss occurs for each degree of deviation from the direct component of solar irradiance. This can be minimized by facing the PV panel always to sun position. The fixed tilt angle can be determined by \( \phi \pm 15^\circ \).
- PV module performance degrades with increasing module temperature. 0.03% to 0.05% efficiency decreases for every 1°C temperature increase without cooling, and reduction in efficiency reaches up to 69% working in 64°C operating temperature. The cooling of the PV panel indicates more energy gain by 18%, 15% and 2.5% by thermoelectric cooling, active water cooling and natural ventilation respectively.
- Glass transmittance decreases by 20% within 45 days without cleaning. Dust density may drop due to tilt angle, rainfall, wind and other environmental parameters. Deposition of dust in humid conditions forms adhesive, sticky mud on the PV panel and causes soiling. The soiling effect can reduce transmittance by 30% for coated glass and 37% uncoated glass after 40 days of exposure in KSA. Pure water acts as the best cleaning and cooling agent and can increase efficiency 15% by robotic spray device.
- Environmental wind speed has both positive and negative aspects. Wind speed of 10 m/s can lower the operating temperature by 3.5°C in the USA. However, in a warm place like in KSA, 10°C reduction is possible at 2.8–5.3 m/s wind flow.
- The materials should be carefully selected to withstand against humid conditions as corrosion of the PV panel occurs due to moisture ingress in humid conditions.
- Even though the installation cost of current PV systems is comparatively high, it is a cost-effective renewable energy source as the operation and maintenance cost is low. As such, the overall life cycle cost and the energy payback period are minimum. The literature review presented in the study would be helpful for the engineers,
FUTURE WORKS

• The optimum use of water will enhance the effectiveness of cooling technology; thus improving the performance of PV module and cost-effectiveness. Further research is warranted to develop the optimum hybrid cooling technology that can reduce the pumping power and water usage. An automated cooling and cleaning technologies with proper sensing systems can be developed.

• More research works can be extended to develop artificial-intelligent models to predict the dust accumulation on the PV surface. This predicted model will be helpful for the investigators to develop an appropriate cooling and cleaning technologies.

• Further research is required to find the appropriate nanomaterials to prevent the dust and soiling on PV module in desert and humid areas.

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