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A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques

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ABSTRACT

The energy yield from the solar photovoltaic plant mainly depends on available solar flux, quality of the related power-conditioning equipment incorporated in the system, technical specifications of the panel, the geographic location and also on the environmental parameters. This study provides a comprehensive review of the effect of environmental factors on the various components of photovoltaic systems. It emphasises the environmental factors such as dust, ambient temperature, wind velocity, humidity, snowfall, hailstorms and sandstorms, which deteriorates the energy efficiency of solar plants and the various failure modes of the panels caused by these factors. Finally, the focus is on the methods to find out different failure modes of photovoltaic panels and the various mitigation techniques to improve the energy yield. These mitigation techniques are essential for positioning of photovoltaic arrays in remote, desert, dusty and areas proximate to higher wind speed. This review provides an outlook for the developers to take precautionary measures before locating the site and designing the solar plants.

1. Introduction

Sunlight, the natural and predominant source of energy, that reaches the earth ‘s surface, fulfils the power necessity of billions of people. Although solar energy is intermittent, it provides higher reliability, energy security, independence, and helps indirectly in reducing global warming. Harnessing of solar energy using ever-evolving technologies exists since the ancient periods. However, the application has recently been boosted in the fields of space heating, water pumping, desalination and power generation using PV modules [1].

A PV cell is a photochemical energy conversion device which converts the energy of light into electricity by photovoltaic phenomena. The number of PV cells connected in series forms a module and various modules connected in series and parallel constitute an array [2]. The efficiency of a solar cell is the ratio of delivered output power to the amount of solar energy striking the surface. Accordingly, the performance of the PV system depends on the power output from the module, which is related to cell characteristics and also on ambient conditions [3]. A PV system primarily consists of solar cells, batteries, inverters, controllers, etc. Different materials of various efficiency and costs are used to make the PV cells, which produces power with the help of auxiliary components when the Sun's light is incident on these cell surfaces. The performance of PV technologies depends on various climatic factors like cumulative solar radiation, cell temperature, operating temperature, wind velocity, natural or artificial shades on the panel, hail, lightning, snow, ice, air-mass, clouds, dirt on PV surface, the latitude of installation, module degradation, etc. The productivity of the PV panels integrated into the system significantly affects the effectiveness of the entire unit and thereby influences the power production rate [4]. The efficiency of the solar panel relies on multiple factors, such as the size of PV array used, type of module, orientation from due south, solar panel pitch, the angle from the horizontal, cable thickness, charge controller, inverter and battery efficiency.

The purpose of the paper is to provide a brief review of the environmental factors like dust, ambient temperature, wind velocity, humidity, snowfall, hailstorms and sandstorms that adversely affect the energy yield of the PV systems. The work reviews the different components of the PV system and the influence of environmental factors on these components. The work highlights the effect of climatic and environmental conditions on PV efficiency and summarises the different module failures. The study focusses on different methods to analyse the degradation mechanism of the PV modules. The review also covers the techniques which could help the customers or investors to carry out precautionary methods to enhance the efficiency of the solar PV

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Abbreviations

3D	three dimensional
AC	alternating current
Ag	silver
Al_2O_3	aluminium oxide
ANOVA	analysis of variance
ARC	anti-reflection coating
BAPCO	bahrain petroleum company
BIPV	building integrated photovoltaic
CCD	charge coupled device
CEEE	centre for energy and environmental engineering
DC	direct current
DLIT	dark lock-in thermography
DUBIT	düzce university scientific and technological researches application and research centre
EDS	electrodynamics screen
EL	electroluminescence
EVA	ethylene vinyl acetate
H·V	high voltage
ILIT	illuminated lock-in thermography
IR	infrared
I-V	current-voltage
LED	light emitting diode
LIT	lock-in thermography
MBRSC	mohammed bin rashid space centre
MENA	middle east and north africa
MIT	massachusetts institute of technology
MOSFET	metal-oxide-semiconductor field effect transistor
NISE	national institute of solar energy
NIT-H	national institute of technology, hamirpur
NOCT	nominal operating cell temperature
NTE	normal terrestrial environment
PCM	phase change material
PEDOT	poly (3,4-ethylene dioxythiophene)
pH	potential of hydrogen
PSS	poly (4-styrene sulfonate)
p-TYPE	positive charge of hole
PV	photovoltaic
P-V	power-voltage
PV/T	photovoltaic/thermal
R&D	research and development
SEM	scanning electron microscope
Si	silicon
SPSS	statistical package for the social sciences
TEM	transmission electron microscope
TiO_2	titanium dioxide
UAE	united arab emirates
UM	university of malaya
URERMS	renewable energy research unit in the saharan region
UV-F	Ultraviolet fluorescence
XRD	x-ray powder diffraction

Nomenclature

A	surface area (m^2)
a and b	constants
am	ante meridiem: before noon
D	degradation rate
dT	temperature difference (°C)
FF	fill factor, a quality indicator of the solar cell
G_r	grash of number
G_T	radiation flux of 1000 W/m^2
h	convective heat transfer coefficient (W/m^2 °C)
H_{cond}	rate of heat transferred per unit cross-sectional area (W/m^2)
H_{conv}	convective heat transfer (W/m^2)
H_{rad}	radiation heat transfer (W/m^2)
I-V	current -voltage
I_m	maximum power point current corresponding to current-voltage curve of a solar cell (A)
I_{sc}	short-circuit current (A)
k	thermal conductivity of the material (W/m °C)
L	length of the solar cells (m)
mm	milli metre
n	number of years
N	nusselt number
N_c	acceptable lightning strikes
N_d	direct lightning strikes
nm	nano metre
P-V	power-voltage
P_m	peak power output of the solar cell (W)
pm	post meridiem: after noon
P_r	prandtl number
R_a	rayleigh number
T_a	ambient temperature (°C)
T_c	operating temperature of the PV module (°C)
T_o	high temperature at which PV module's efficiency reduces to zero (°C)
V_m	maximum power point voltage (V)
V_{oc}	open circuit voltage (V)
W	watt
x	direction and the distance (m)

Greek symbols

€	euro sign
β_{ref}	temperature co-efficient (%/°C)
γ	solar radiation coefficient
ΔT	difference between the receiver and ambient temperature (K)
ε_{eff}	emissivity of the surface
η_c	cell's electrical efficiency
η_i	PV panel's operating efficiency
η_o	nameplate efficiency
η_{Tref}	electrical efficiency of the module at the reference temperature T_{ref}
σ	stefan-boltzmann constant (W/m^2 K^4)

systems. The mitigation techniques include different cooling mechanisms, lightning protection systems and various approaches to remove soiling from the surface of the panels. Although this paper is focused mostly on silicon-wafer based PV modules, some of the reviews may also be related to certain thin-film PV modules.

2. PV system and the influence of environmental factors

A solar PV system consists of solar panels, inverters, batteries, wirings, power conditioning units and the electrical load. Weather, climatic conditions, design and installation of the PV components have a considerable role in delivering the output power from a PV system. The following sections discuss the effect of environmental factors on various PV components.

2.1. PV module

The life of a PV module depends on reliability (prone to premature failure) and durability (slow degradation rate), which in turn depends on the degradation modes. Outdoor exposure causes severe environmental stress to PV modules, and as a result, the output power is hampered. Environmental factors widely influence the module stability and the prediction of the degradation is complex as various stress will be triggered through various mechanisms. Degradation of the PV module is mainly affected by four climatic factors, i.e. temperature, irradiation, humidity and mechanical stress which further induces degradations such as corrosion, discolouration, delamination and breakage [5]. The permeability of the back sheet of the PV module enhances at higher temperature and humidity, as the module's temperature is always greater than ambient temperature. Moisture entering the module degrades the adhesion material between the PV cell and the contact metal, causing corrosion and hence results in leakage of the current. The moisture ingression due to higher humidity and temperature corrodes the metal surface and increases the delamination between the solar cell and encapsulating material. The UV rays degrade the encapsulant material of the PV module (EVA) causing yellow or brown discolouration. The change in colour enhances the optical transmission losses and hence deteriorates the performance of the module. Other climatic factors such as snow and wind create mechanical load on the PV module. Hailstorms cause damage to glass modules, and sandstorm causes abrasion to the module surface [6].

2.2. Metallic structures

PV module frames being metallic structures are prone to lightning strikes and must be properly grounded for reducing the damage to the PV systems. Aluminium or galvanised steel structures provide adequate resistance to wind and other climatic conditions. The design and installation of these metallic structures must be done cautiously to meet the wind speed requirements of the site; else the panels will be lifted off from the structure.

2.3. PV system wire

PV wires are single conductor electrical wires to connect PV panels with other electrical components in a PV system. The proper selection of the wires and their periodic maintenance influences the PV performance positively. Usage of substandard cable that is inappropriate to the environmental conditions increases the chances of failure of the PV system. The PV wires must be flexible, waterproof, UV-resistant and also withstand the temperature fluctuations due to outdoor exposure. The exposed wires suffer ageing factors due to chemical elements, solar radiation, microbial growth and temperature. Wires or cables in the outdoor environment must be protected with flexible metal conduit to protect from sunlight and rain. Fixed cables in underground conduits should be sealed at both ends. Otherwise they will saturate with water resulting in damage of insulation resistance. Prolonged immersion further results in current leakage and short circuits. Despite the rating provided by the manufacturer such as UV-resistant and temperature withstanding capability, cables undergo ageing (the outer sheath of the cable becomes brittle and affects UV-stability) over some time due to continuous exposure to high radiation. Cables exposed to snow cover are also prone to damages. The presence of chemicals in the soil develops chemical stress on the PV cable through the cracks developed on it. Moisture in the atmosphere causes short-circuits and corrosion of the copper conductors. Selection of durable cables that meet the certifications and their proper installation rectifies the PV failure to some extent.

2.4. Battery

The inclusion of batteries in a PV system for energy storage is an intelligent solution to overcome the intermittent nature of solar energy. The battery's lifetime mainly depends on its components, charging methods, temperature, the frequency of discharges and design of the PV system. Despite the advanced technology, a powerful battery-storage system, which can withstand the extreme heat and cold climate is questionable. Operating temperature is an important parameter to be considered while sizing the battery bank. The battery uses electrochemical reaction, and at high temperature, the chemical reaction enhances causing a deterioration in battery life. But, at a higher temperature, the capacity and the performance of the battery increases. However, operating the battery at a lower temperature reduces the reaction rates, performance and capacity, but the life of the battery increases. Hence, the selection of operating temperature is inevitable for the proper functioning of the PV system. One possible solution to maintain the battery temperature is by passive cooling (insulation fans or water circulation systems) and active cooling systems (air conditioning) which improve the service life of the battery. However, the energy return factor for the battery increases with the daily cooling process of the battery room [7]. Batteries suffer a considerable loss in cold climatic conditions due to degradation of the plating, lower energy and power capacity. At lower temperatures, battery faces a slowdown in chemical reactions causing a lower electrolyte conductivity. These processes decrease the energy and power of the cell thereby causing a performance failure of the batteries in cold climate. Thermal management of the battery is a viable option to enhance the lifespan of the batteries in cold countries [8]. Active or passive heating based on air, liquid and phase change materials effectively warms the battery to ambient temperature before start-up.

2.5. Inverters

The brain of the PV system, the inverters convert the direct current output from the PV modules to alternating current. The operating environment (indoor or outdoor), installation conditions such as ambient temperature, the necessity of water or dustproof, the audible noise level of the inverter and power quality regulations influences the inverters conversion efficiency. At high-temperature locations, installing inverters in a closed utility room raises the temperature of the room as well as the inverter which in turn reduces its life and deteriorates the performance. Proper venting and airflow are necessary to meet the adequate operating temperature provided by the manufacturer. Inverters kept near to residential areas delivers heat to surrounding place. However, for a cold climate, this would help to maintain the ambient room temperature. The unit must be installed in locations protected from environmental conditions such as humidity, temperature, water vapour and dust particles for proper working and to meet the specifications provided by the manufacturer. The inclusion of a surge protection device helps to bypass the high voltage caused by lightning in areas where grounding is not feasible or locations prone to lightning.

3. Factors and effects of environmental conditions on PV efficiency

The efficiency and reliability with which a solar PV system produces its energy yield depend on various variable and invariable parameters. The effectiveness of the PV system improves by altering some variables by the user, as specified by the manufacturer. The two essential components providing optimum yield are the PV panel and the amount of solar radiation incident on the PV surface. The variable parameters that improve the performance of the PV module include materials implemented for PV cell manufacturing and coatings to protect from environmental conditions. The invariable components comprise the

Table 1
Effects of dust on PV performance

Reference	Duration	Dust influence	Location	Type of cell
Said and Walwil [17]	Five weeks	PV output power reduced by 6% after five weeks and glass cover transmittance decreased by 20% after 45 days of exposure. Also, 5 g/m^2 of dust deposited on PV glass surface.	Dhahran- Saudi Arabia.	Mono-crystalline
Saidan et al. [18]	One day, one week and one month	The average degradation rate of efficiency is 6.24% (1 day), 11.8% (1 week) and 18.74% (1 month).	Baghdad city in Iraq.	Mono-crystalline
Guan et al. [19]	Two days	Relative transmittance decreased by 20% (8 days of dust deposition-29, April to 6 May 2014). For dust densities of 5.06, 7.58 and 12.64 g/m^2, the average relative output power rates (29 April 2014 and 30 April 2014) were 93.69%, 90.49%, and 79.38%.	Chang'an District, Xi'an, China.	Poly-crystalline
Paudyal and Shakya [20]	150 days	PV efficiency reduced by 29.76% and the density of the deposited dust was 9.67 g/m^2.	Tribhuvan University, Lalitpur, Nepal.	Poly-crystalline
Ramli et al. [21]	Four weeks	PV power declined by 2.05%, 10.8% and 87.29% after one, two and four weeks respectively.	Surabaya, Indonesia.	Mono-crystalline
Gholami et al. [22]	70 days	Transmission coefficient declined by 25%. Dust density varied from 4.0599 g/m^2 and 10.3129 g/m^2 facing northwest with 90° tilt angle and facing north with 15° tilt angle respectively.	Isfahan University of Technology, Iran.	–

efficiency of the cells employed, characteristics of the glass cover of the panel, optical stacking losses and the response of temperature concerning the output voltage of the PV system.

In addition to this, various environmental parameters and the design of the installed panel also affects the solar panel efficiency and thereby hinders the PV systems to deliver the energy output uniformly. The adjustable ecological elements include the solar reflector materials (silvered glass mirrors, aluminized reflectors, and front-surface mirrors), which improves the solar gain without adding to PV collector heat dissipation; local pollutants like potential toxic pollution from exhaust fumes, carbon dioxide, ozone, water vapour, aerosols; and proper installation of panels to withstand the pressure of hurricanes. There are also specific natural environmental characteristics which affect the insolation and are unalterable. These include the intensity of solar radiation, dust, wind velocity, precipitation, moisture level and atmospheric temperature. The flexible design elements affecting the energy yield from the PV panel include the incorporation of solar trackers and PV mounting based on the tilt angle. The stable aspects affecting the installation design contains the vertical or horizontal placement of PV panels, orientation between south-east and south-west directions, exact geographic coordinates, and altitude to mount the PV module. The following section discusses the various atmospheric parameters responsible for deteriorating the maximum energy yield from the PV module and its impact on the panel efficiency.

3.1. Dust

Dust is a general term applied to a particulate matter whose diameter varies between 0.10 μm and 1000 μm. Dust deposition is a natural phenomenon that adversely affects the energy yield from the solar panels by either absorbing or reflecting the solar radiation. Dust accumulation mainly includes the growth of organic species like bacteria and fungi, birds nesting, bird droppings, corrosion due to bird feces, contamination by plant products, chemical weathering process, industrial carbon, cement, limestone, airborne particulates, microfibers from carpets and fabrics. The conditions which help the dust to stick on the panel are air velocity, wind direction, humidity, rainfall, the frequency of dust storms, ambient temperature, surface finish, tilt angle, soil type and surrounding vegetation [9].

The characteristics of dust involve its chemical, electrostatic, biological and physical properties. Dust settlement or accumulation on the solar panel depends on its physical properties such as shape, size, weight and environmental conditions. The tiny dust particles settle faster than the coarser ones [10], and due to Coulomb force, the charged particles tend to gather more than the neutral particles [11]. Based on the environmental conditions, the dust's chemical, as well as mineral composition, varies from one location to another [12]. The strength of adhesion [13] between the PV panel surface and the dust particles depends on the dust removed by wind, and the effect is inversely proportional to dust particle diameter. The environment, as well as the weather conditions, also influence the dust sedimentation and the deposition characteristics. Dust accumulates on the PV surface as occult deposits, dry deposits, and wet deposits. Occult deposits occur when moisture in fog, mist or cloud, high relative humidity [13] and dew [14] settles on PV panel surface. The dry condition causes the wind to carry away the dust particles, and the Coulomb force of attraction gathers more dust, whereas the repulsive force suspends the particles in air blown by the wind. The wind speed influences the settlement of soiling on the PV surface positively and negatively based on the wind speed, direction, source of dust and the PV installation [15]. Like the wind, the rainfall also helps in improving (cleaning the PV surface) and deteriorating (air pollutants trapped due to precipitation on the PV surface) the efficiency of the PV panel at the same time. Higher ambient temperature increases the humidity content which assists the dust particles to stick to the PV surface [15]. The dust deposition on the module surface decreases when the PV panels are installed at a larger tilt angle due to the effect of gravity [10]. The location of PV installation also affects the dust accumulation as the deposit rate is higher near to industries, volcanic zones, and areas prone to sandstorms [16].

Where dust falls on the surface of the PV panel, the maximum yield from the PV modules is categorised either as alterable or unalterable factors [9]. Dust affects the energy efficiency of the PV system in different ways. Table 1 [17–22] shows some of the published work about the effect of soiling on PV performance. Dust reduces the amount of sunlight incident on the panel surface by scattering the incoming solar radiation as the size of dust particles are larger than the wavelength of the radiation emitted by the Sun. Researchers [23] have noticed a reduction in PV efficiency of 60% due to the presence of dust and air pollutants in the atmosphere. The thick layer of dust on the module surface alters the panel's optical properties by increasing the light reflection, reducing the transmissivity and thereby decreasing the PV panel output. The reduction in transmittance results in particle shading due to dust accumulation on the panel surface based on dust size and density. This partial shading causes variation in the electrical characteristics of the PV array resulting in power loss due to reverse biased cells and a subsequent reduction in fill factor [24]. Deposited dust also causes a difference in temperature between the cleaned panel and the dust deposited panel, hence results in slight variation in short-circuit current and a considerable reduction in open circuit voltage. An experiment conducted on polycrystalline Si solar cells shows that the dust deposited on the panel surface reduces the glass panel's transmittance, and the temperature of the module, which decreases the PV module's output power [19]. The accumulated dust on the PV panel causes degradation of the solar spectrum reaching the module surface. This reduction results in attenuation of the entire solar range from ultraviolet to visible due to absorption, reflection and scattering of light by the accumulated dust [25].

3.2. Temperature

In PV systems, ambient temperature plays a vital role in deriving the output power and the efficiency of the PV module, as it is linearly dependent on operating temperature. Based on the type of cell employed in the solar module, the PV panel converts nearly 6–20% of the insolation incident on its surface. The increase in the ambient temperature enhances the PV panel's temperature thereby reducing the efficiency of the module. The climatic parameters like atmospheric temperature, wind speed, wind direction and cloud patterns strongly influence the temperature of the panel, but the rate at which the temperature changes depends on the type of PV material used and the way the PV panel is mounted. When the temperature of the panel increases, there is a decrease in voltage output of the module and an increase in current by a small amount, which reduces the power output of the entire PV system. Table 2 [26–30] highlights some of the published literature about the influence of ambient temperature on PV efficiency. The impact of temperature on the PV cell/module is related to the fundamental equation as

$$P_m = V_m I_m = FF \times V_{oc} I_{sc} \tag{1}$$

When temperature increases, both the V_{oc} and FF reduces with slight increase in I_{sc} which results in a linear relation for cell's electrical efficiency given by Ref. [31],

$$\eta_c = \eta_{T_{ref}} [1 - \beta_{ref}(T_c - T_{ref}) + \gamma log_{10} G_T] \tag{2}$$

A traditional linear expression for the module efficiency after equating γ value to zero is given by Ref. [32],

$$\eta_c = \eta_{T_{ref}} [1 - \beta_{ref}(T_c - T_{ref})] \tag{3}$$

$\eta_{T_{ref}}$ and β_{ref} are manufacturer specified values of which the later depends on PV material and T_{ref} given by, $\beta_{ref} = \frac{1}{T_o - T_{ref}}$ .The exposure of solar panels in the open atmosphere causes an increase in module temperature, and it is necessary to find the expected operating temperature of the PV module to figure out the output power of the solar cell. The NOCT which is the temperature attained by the PV module with no-load connected and operating in NTE are listed below [33]:

Solar flux on the cell surface: 800 W/m^2,
Air temperature: 293.16 K (20 °C),
Average wind speed: 1 m/s,
Mounting: Open back side and tilted to solar noon.

The approximate expression to find out the operating temperature of the PV module for irradiance, G_T (W/m^2) is given by,

$$T_c = \left[T_a + \left(\frac{NOCT - 20}{800} \right) \times G_T \right] \tag{4}$$

The operating temperature has a tremendous effect on the performance and efficiency of the solar cell. An increase in the cell temperature results in degrading the performance of the panel and thereby reduces the effectiveness of the module. The mitigation section discusses the various techniques to improve efficiency by lowering the operating temperature.

Table 2

Effects of temperature on PV performance

Reference	Temperature effect	Location	Type of cells
Rahman et al. [26]	For every 100 W/m^2 increase in radiation, solar cell temperature improved to 4.93 °C and 2.64 °C respectively with and without cooling. For 1000 W/m^2 irradiation and 80 L/h water cooling system, solar cell temperature reduced to 22.4 °C, output power and efficiency improved by 8.04 W and 1.23% respectively.	UM, Malaysia.	Mono-crystalline
Touati et al. [27]	For monocrystalline PV, during the day (8:30 a.m. to 15:45 p.m.), the change in temperature (41.9, 48, 49.9 and 40.4 °C) increases PV efficiency (0.71, 0.76, 0.78 and 0.8). For amorphous PV, during the day (8:30 a.m. to 15:45 p.m.), the change in temperature (42.9, 48.4, 45.4 and 40.9 °C) increases PV efficiency (0.385, 0.383, 0.358 and 0.616).	Doha, Qatar.	Mono-crystalline and amorphous
Rahman et al. [28]	The electrical efficiency decreased by 0.22% for 1 °C increase in solar cell temperature. Similarly, the solar cell temperature and output power increased by 3.82 °C and 3.14 W, as the solar irradiation increased by 100 W/m^2. Incorporation of water cooling system enhanced the performance by 15.72%.	UM, Malaysia.	Mono-crystalline
Gaglia et al. [29]	PV voltage dropped between 91 and 97 mV/°C for 400 and 1000 W/m^2 irradiance levels which are higher than the laboratory standard conditions (73 mV/°C). The instantaneous efficiency reduced to 7% from 10% for a voltage drop of 5 V.	Athens, Greece.	Multi-crystalline
Elibol et al. [30]	An increase of 1 °C ambient air temperature increased the efficiency of amorphous crystalline panels by 0.029%, polycrystalline panels by 0.033% and decreased the productivity of monocrystalline panels by 0.084%.	DUBİT in Düzce Province, in Turkey.	Mono-crystalline, poly-crystalline and amorphous crystalline

3.3. Wind velocity

The performance of the PV cell is sensitive to wind velocity in both positive and negative ways. Wind carries away the dust particles for tilted PV installations and reduces the dust deposition on the PV surface thereby influencing positively. Table 3 [34–38] provides some of the published work about the influence of air flow on PV performance. However, increased wind speed carries the dust and other sand particles on to the module surface, thereby deteriorating the PV performance [10]. The outdoor exposure of the solar panels results in the generation of power as well heat exchange process between the PV collector and the external environment. The temperature at which the panel operates depends on the equilibrium established between heat generated by the PV module and the energy lost to the external environment due to conduction, convection, and radiation as shown in Fig. 1 [10]. Under steady state conditions, the one-dimensional conduction defines the transfer of heat taking place within the body when there is a difference in temperature, which is directly proportional to the temperature difference (dT) through a distance (x) as in equation (6) [10]:

$$H_{cond} = -k\frac{dT}{dx} \tag{5}$$

The negative sign implies a positive heat flow in the direction of the negative temperature gradient ($\frac{dT}{dx}$). Heat loss due to radiation happens when there is a temperature difference between the solar collector and the atmosphere. The radiation heat transfer is given as follows,

$$H_{rad} = \frac{Q_{rad}}{A} = \varepsilon_{eff}\sigma\Delta T^4 \tag{6}$$

Convection is the mode of heat transfer between two bodies utilising flowing fluid. As far as the solar panel is concerned, the heat loss due to convection occurs due to the flow of wind across the panel surface. The general equation [10] to explain the convective heat transfer is:

$$H_{conv} = \frac{Q}{A} = h\Delta T \tag{7}$$

The convective heat transfer coefficient is directly proportional to the *N, Nusselt number* and thermal conductivity and is inversely proportional to the gap width between the glass panes of the panel. The term h, *convective heat transfer coefficient* [10] defined through N, is a ratio between convective and conductive heat transfer and is a function of G_r, *Grashof number* and P_r, *Prandtl number*.

$$N = \frac{hL}{k} \tag{8}$$

$$N = a(G_rP_r)^b \tag{9}$$

R_a, *Rayleigh number* expressed in terms of G_rP_r as

$$R_a = G_rP_r \tag{10}$$

At constant P_r and variable G_r the laminar and turbulent flow observes a Rayleigh number in between 10^7 and 10^9. The energy conservation is the fundamental principle of heat transfer. So applying the law of conservation of energy,

$$H_{cond} = H_{conv} - H_{rad} \tag{11}$$

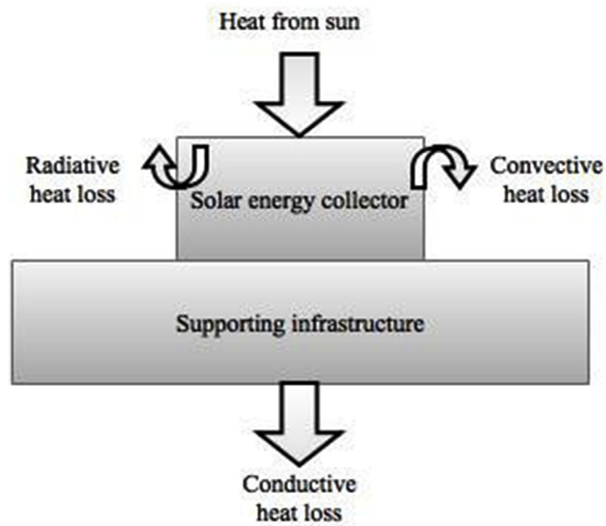

Fig. 1. Heat transfer phenomena in a photovoltaic cell (adapted from Ref. [10]).

Hence, when there is an increase in wind velocity, the temperature of the air decreases, which in turn reduces the operating temperature of the solar cell. This enhancement in air flow causes an increase in the amount of heat loss from the panel due to conduction, convection, and radiation. In this way, the air velocity works positively to improve the performance and efficiency of the solar cell [39].

3.4. Humidity

The effect of humidity on PV performance strongly depends on the suspended water vapour droplets present in the atmosphere. Prolonged exposure of PV panels to humidity can cause moisture ingression which results in encapsulant delamination. Tan et al. [40] experimentally investigated the degradation in PV cell when subjected to a humid environment. Upon the increase in experiment duration, the moisture inside the PV cell damaged the interfacial adhesive bonds causing delamination and higher ingress path thereby resulted in passivation loss. The study revealed that the short circuit current showed a significant decline than the open circuit voltage causing severe degradation in maximum output power. Touati et al. [27] found that the type of panel used also influenced the PV performance while studying the effects of relative humidity on the panel's efficiency. The authors examined the impact of relative humidity and compared the performance between monocrystalline and amorphous PV systems. The study showed that the amorphous PV panels are critically affected by temperature and relative humidity than the monocrystalline PV modules. This decrease in efficiency indicated that the monocrystalline PV panels are robust against climatic factors such as relative humidity and temperature. Humidity also influenced the incoming solar radiation causing a reduction in irradiance level due to reflection, diffraction, and refraction by the water droplets present in the atmosphere. Gwandu and Creasey [41] analysed

Table 3
Effects of air velocity on PV performance

Reference	Air velocity impact	Location	Type of cells
Said et al. [37]	A higher module temperature for any level of wind and radiation ranging from 200 to 1200 W/m^2.	Saudi Arabia	Mono-crystalline
Kurnik et al. [34]	The difference between module and the ambient temperature reduced to half the value for any non-zero conversion efficiency, when the wind speed improved from zero to 12 m/s.	Slovenia.	–
Kaldellis et al. [38]	At a wind speed higher than 3.5 m/s, the value of Ross coefficient reduced from 0.03 ± 0.005 to 0.015 ± 0.005.	Greece.	Poly-crystalline
Gokmen et al. [35]	Wind speed increased the energy estimates by 3.5%.	Denmark.	Poly-crystalline
Goverde et al. [36]	Wind speed reduced the temperature between 4 and 5 °C near the leading edge of the PV module.	Belgium.	Multi-crystalline

the variation of solar radiation intensity with humidity to investigate the efficiency of the PV module in a humid atmosphere of tropical Sudan Savannah region. The authors noticed a non-linear difference of open circuit voltage with radiation level and a linear variation of short-circuit current. The area is prone to high wind speed which lowered the module temperature and hence compensated for the lower irradiance level with higher humidity. Table 4 focusses on the impact of moisture on PV productivity [26,27,40,42,43].

3.5. Snowfall

The PV technology in the colder countries of the world faces severe threats due to hail and snowfall. The snow and ice build-up on the panel surface restricts the sunlight from reaching the solar cells and hence reduces the energy production. Experimental studies have found that the tilt angle, the orientation of the PV module and meteorological factors influences the annual and monthly PV system performance [44]. Powers et al. experimentally investigated the influence of various tilt angle on the reduction in energy loss due to snow cover from regularly cleaned as well as uncleaned PV panels. The output showed a decrease in the annual energy production of 12%, 15% and 18% for 39°, 24° and 0° tilt respectively. The significant finding from this research work was that the reduction in power loss is a function of snow coverage on the PV panel surface and tilt angle of the PV array [45]. Marion et al. investigated the energy loss from the PV system due to snow coverage for six PV systems installed in Colorado and Wisconsin for the winters of 2010–2011 and 2011–2012. The study found a reduction in energy loss of 90% and a decrease in annual energy production from 1% to 12% [44]. Table 5 addresses the impact of snowfall on PV productivity [44–48].

3.6. Hailstorms

Hail is precipitation from the sky as larger pellets or balls of ice. Hail storms can cause a severe threat to PV modules by developing cracks in the cell [49] and eventually breaking the PV panel glass [50] which results in reduction in efficiency. The fast-moving hailstones provide considerable damage to inner solar cells without showing exterior damage. This process known as micro-cracking could degrade the PV system's output. Forman [51] investigated the 11,000 PV panels installed by the MIT Lincoln Laboratory in the field sites in the United States. The study found that almost 320 electrically failed modules were removed due to cell crack, solder joint failure, shorted cells or interconnects and broken interconnects. Half of the inspected PV panels developed impact cracks due to hail. Muehleiden et al. [52] experimentally monitored the impact of hailstone on the degradation nature of the PV modules. The authors tested three PV plants in the south of Austria that were affected with 40 mm diameter hailstorm and found visible damage of the PV glass panels. The UV-F imaging and EL measurement confirmed the fully fractioned cells, line-shaped cracks and cross-shaped micro-cracks in panels. The power loss found in these modules was around 30%, which was further confirmed with parallel power measurements.

3.7. Sandstorms

Sandstorms are hazardous weather, where the sand particles are blown from surface to the air making the air turbid. PV panels installed in desert areas are exposed to frequent sandstorms. Sandstorm increases the deposits of dust on the panel surface and makes the surface opaque causing a significant reduction in energy output. Mostefaoui et al. [53] studied the influence of sand dust and sandstorm on the PV panel efficiency in the desert area of the city of Adrar, the south of Algeria. The PV panels were exposed to the outdoor climate for six months without cleaning, and after that, these panels were cleaned using glass wiper and water. The study showed a reduction in PV efficiency with lower current-voltage (I-V)/power-voltage (P-V) characteristics and performance parameters on a sandstorm day than a clear day. Bouraiou et al. [54] evaluated the influence of partial shading and sand accumulation on PV panels in a desert environment for two months in the city of Adrar. The study showed a reduction in output from 79.7 W to 16.45 W due to partial shading. The continuous exposure of the panels in the desert environment degraded the modules resulting in discolouration of the encapsulant, and delamination. Table 6 focusses on the impact of sandstorm on PV productivity [53,55–59].

4. Defects in PV modules caused by environmental factors

The lifespan of the PV module depends on the quality of the module and the climate where the panels are installed. The performance of the PV system is greatly affected by failure modes and degradation, and its evaluation in outdoor and indoor conditions is essential to design the prediction model. The subsequent section describes the various failure modes of the PV systems triggered by different environmental factors.

4.1. Discolouration

The discolouration of the PV encapsulant (EVA) upon continuous exposure to sunlight is a major contributor to power degradation in PV system [60]. This discolouration eventually reduces the sunlight reaching the PV panels. Four different silver salts [61] such as silver phosphate, silver sulphide, silver carbonate and silver acetate are responsible for the discolouration. They form crystallites on the front surface causing metallization of cells in the PV modules. The higher humid atmosphere, ambient temperature and the quality of the encapsulant effectively increase the discolouration on the PV surface and

Table 4

Effects of humidity on PV performance

Reference	Humidity impact	Location	Type of cells
Rahman et al. [26]	PV output power reduced to 3.16 W with 20% increase in relative humidity and to 1.58 W with 10% increase in relative humidity.	UM, Malaysia.	Mono-crystalline
Touati et al. [27]	For monocrystalline PV, during the day (8:30 a.m. to 15:45 p.m.), a reduction in relative humidity (28-22%) increased the PV efficiency (0.71–0.8). For amorphous PV, during the day (8:30 a.m. to 15:45 p.m.), a reduction in relative humidity (28-22%) increased the PV efficiency (0.385–0.616).	Doha, Qatar.	Mono-crystalline and amorphous
Kazem and Chaichan [42]	The PV array power reduced by 43.48, 48.42 and 58.38% and PV panel voltage by 23.18, 24.88 and 25% during July, August, and September respectively. An increase in relative humidity from 67 to 95% decreased the current by 44.44%.	Sohar city, Oman.	Mono-crystalline
Tan et al. [40]	Degradation of short-circuit current and maximum power output. Delamination of the encapsulant, weakened inter-facial adhesive bonds, increased ingress path, sample warpage due to swelling of encapsulant and loss of passivation.	Singapore.	Amorphous
Kawano et al. [43]	Spatially inhomogeneous PEDOT: PSS layer, the formation of insulating patches, loss of device current and device efficiency.	–	Organic solar cells

Table 5

Effects of snowfall on PV performance

Reference	Snowfall impact	Location	Type of cells
Meyta and Savrasov [46]	Performance reduced by 13% on a clear day and 40% on a cloudy day	Russia.	Mono-crystalline
Marion et al. [44]	Production loss is 1–12%	Colorado and Wisconsin	Poly-crystalline
Andrews et al. [47]	Short circuit current loss, power reduction	Canada.	Amorphous and crystalline silicon
Heidari et al. [48]	29–34% annual energy loss	Michigan.	Poly-crystalline
Powers et al. [45]	Annual power losses of 12–18%	United States and Canada.	Poly-crystalline

the grid fingers.

4.2. Corrosion

Corrosion is the electrochemical reaction of the metal with the moisture from the surrounding environment. This reactivity of metals in the PV modules causes cracks in solder bonds, the formation of Ag fingers, corrosion of the cell, and degradation of the antireflection coating [62]. Higher temperature, humidity [63], system voltage and moisture absorption of the encapsulant accelerate the corrosion and oxidation process which in turn increases the series resistance, deteriorates the fill factor and reduces the output power from PV systems.

4.3. Glass breakage and cracking

Glass breakage and cracks are formed by mechanical stress, hail and stone throwing, transportation, thermal stress due to outdoor exposure, maintenance and handling [5]. Micro-cracks formed while manufacturing the PV modules are difficult to notice with the naked eye. These cracks cause moisture intrusion, chances of electrical shock and power reduction [64]. The PV panel breakage also increases the corrosion, delamination and discolouration.

4.4. Snail trails

The PV modules exposed to the outdoor environment for several months develop discolouration of the contact fingers across the cell [65]. The back sheet foils due to water vapour permeability and results in irregular dark stripes called snail trails or snail tracks. This phenomenon significantly impacts the PV output, and the researchers are yet to identify the actual reason behind the formation of snail trails.

4.5. Anti-reflection coating (ARC) deterioration

The formation of dust and dirt on the module surface significantly damages the antireflection coating. This damage causes variations in the spectral transmittance in the visible range of 600–700 nm. The dust accumulation causes a drastic power reduction in antireflective modules [37].

4.6. Hotspots

Bird droppings, leaves and dust patches hamper some of the cells of the PV module and block the current generated from other cells. This shading operates the diode in reverse bias mode, heats the cells and causes hotspot, which damages the PV module. Dhimish et al. proposed the mitigation technique for hot spots to enhance the PV power output using the power-metal oxide semiconductor field effect transistor (MOSFET). The method sustains a portion of the reverse bias voltage across the shaded cells [66].

4.7. Delamination

Delamination of the encapsulant is the major degradation in PV module due to adherence loss between encapsulant-glass, encapsulant-cell and encapsulant-back sheet delamination [67]. The presence of oxygen and water diffusivity of the encapsulant protect the PV cells from UV radiation and external weather conditions. The continuous exposure of the UV radiation, humidity and ambient temperature causes EVA to change its colour to yellow or brown [6]. This cell bleaching eventually forms bubbles at the EVA, back sheet and finally corrodes the PV cell resulting in poor performance of the PV system.

5. Detection of failure in the PV module

All the PV panels undergo degradation phenomena due to the ageing process. Over the years this results in loss of power from the PV systems and an overall decrease in power due to the failure of the single solar cell in the module. The special events that these panels undergo when it experiences degradation are called failure modes. The following equation provides the degradation rate (D) as

$$D = \frac{\eta_o - \eta_i}{N} \tag{12}$$

The classification of the faults in the PV modules comprises optical degradation, electrical degradation, and non-classified defects. The optical degradation includes delamination and formations of bubbles, breakage of front glass covers and discolouration of the encapsulant. Poor soldering, shading, shunts and short-circuited cells, cell cracks and broken interconnection ribbons comes under electrical degradation. The non-classified faults consist of a defective by-pass diode, open circuited submodule and potential induced degradation [68]. The investigation of the various degradation process is dragging attention nowadays due to the broad deployment of large-scale PV systems. The following section explains some of the techniques such as visual

Table 6

Effects of sandstorm on PV performance

Reference	Sandstorm impact	Location	Type of cells
Mostefaoui et al. [53]	Particle deposition density of 2.6 g/m^2, shading effect, power reduction, lower short circuit current	Saharan of Adrar, Algeria.	Mono-crystalline
El-Nashar et al. [56]	Drop in transmittance, 60% annual production drop	Abu Dhabi, UAE.	–
Dabou et al. [57]	Lower energy yield, irregular inverter, module and system efficiency	South Algeria.	Mono-crystalline
Semaoui et al. [58]	Relative loss of short-circuit current of 1.75%, power loss	South Algeria.	Mono-crystalline
Bouraiou et al. [55]	Partial shading, Power loss	South-west of Algeria.	Mono and Poly-crystalline
Cabrera et al. [59]	Higher transmissivity (T), reflectivity (R) and short-circuit current losses	Germany and Chile.	Different cell types

inspection, measurement of module I-V characteristics, IR imaging, LIT, EL imaging and UV fluorescence imaging [69] to detect the flaws and damages in the module.

5.1. Visual inspection

After prolonged use of the PV system, the PV module causes some defects which hamper the electrical characteristics of the PV system. These defects result in yellowing, delamination, formation of bubbles and cracks, burnt cells and flaws in the anti-reflective coating, causing potential risk to the performance of the modules. Visual inspection is the best and the first method to find out the defects with human's natural eye under natural sunlight. This assessment must be done to differentiate the layers at various angles where the fault could probably occur due to reflected images [70]. Bouraiou et al. [55] visually inspected the detectable failures of 608 PV modules inside the site of Saharan medium fields and the PV central of Melouka under real operating conditions in a desert environment in Algeria. The authors observed a non-optimal tilt of 17°, breakage of glass panels due to high temperature and accumulation of sand dust on the lower edge of the module in Melouka PV central field. In addition to this, EVA discolouration and corrosion of metallization damaged the PV panels (Fig. 2). The PV panels in Saharan field underwent snail trail effect, glass scratches, corrosion of metallization, EVA discolouration, cracking of solar cells, busbar corrosion, and delamination.

5.2. Indoor testing using the solar simulator

The usage of the solar simulator and exposing the panel to natural sunlight helps in determining the I_{sc}, V_{oc}, V_m, FF, series and shunt resistance, cell and the module efficiency, I-V and P-V characteristics. These computations help in finding out the features of modules with different technologies like mono, poly and thin film technologies by exposing the panels to homogeneous light distribution with continuous light spectrum. The environmental conditions must be observed to maintain a consistent temperature to reduce the voltage and current correction due to the specific temperature coefficient of each panel [70]. Sharma and Chandel [64] investigated the 1 kW PV system consisting of 10 modules of 100 W multi-crystalline Si modules installed on the rooftop of CEEE, NIT-H in the Himalayan region of Himachal Pradesh, India. The authors conducted indoor testing of the modules using, Endeas Quick Sun 700 class-A, Sun simulator and compared the panel ratings after 2.5 years of outdoor exposure. The study shows an average power degradation in module No.2, 6 and 10 reached 50% when compared to other modules. Due to the reduction in V_{oc} values, module No. 2 and 10 underwent power degradation while the decrease in I_{sc} and FF caused a reduction in power for module No.6 (Fig. 3).

5.3. Infrared (IR) imaging

The contactless and non-destructive method, IR imaging measures the electrical and thermal failures in the PV module, where the measurement is carried out under steady-state conditions. The technology uses IR camera sensitive to black body emission in the range of 3.6–5 μm range. By exposing the panels to thermal or IR imaging, the poor, as well as shunted cells, appear as bright hotspots when compared to other cells due to heat dissipation. By inducing an external current in the forward direction or by applying light to the PV module, the panels show a temperature gradient which helps in analysing the thermal images. These images assist in finding out the areas where the potential problems could occur [70]. Rajput et al. [71] analysed the degradation modes and mechanism of 90 mono-crystalline silicon PV modules installed on the rooftop of the guest house of NISE, Gurgaon, India after 22 years of outdoor exposure. At an irradiation level of 800 W/m^2 on a sunny day, the PV module array underwent thermographic measurements using EasIR-4000 Thermal Imager. The angle of view was kept at

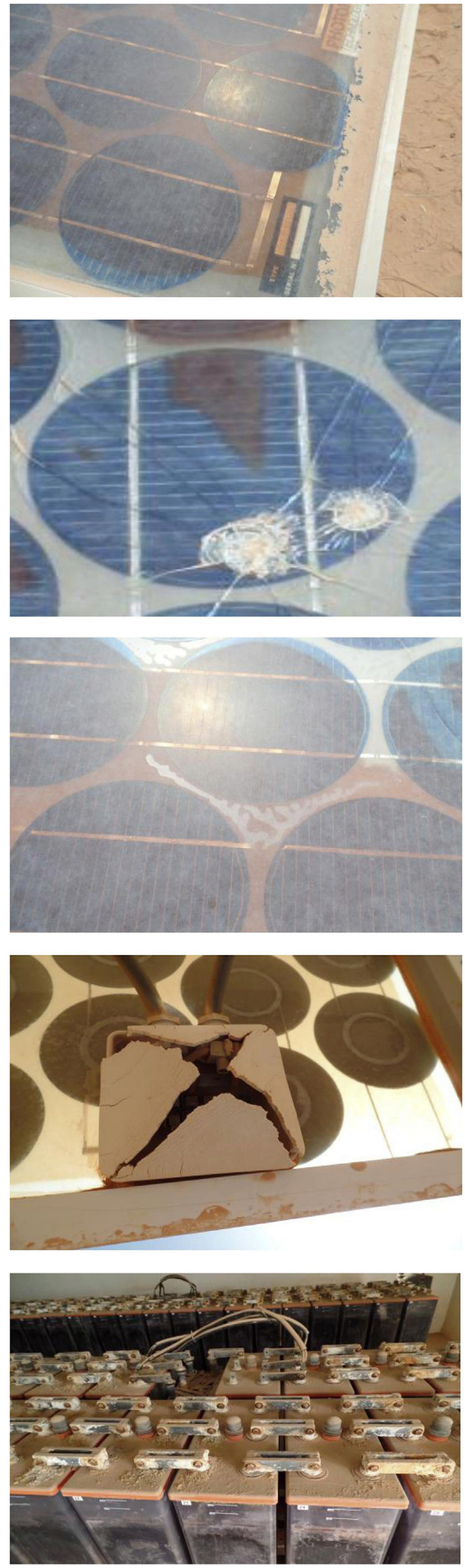

Fig. 2. Important defects found in the PV panel in Melouka central (adapted from Ref. [55]).

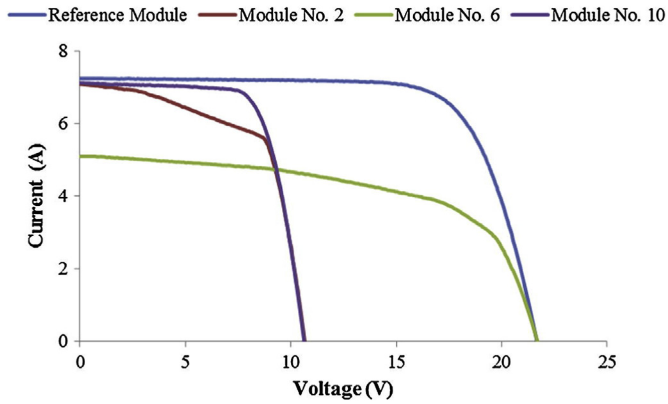

Fig. 3. Comparison of the I-V (current-voltage) characteristics of the degraded modules (No:2, 6 and 10) with the reference module (No:7) (adapted from Ref. [64]).

90° while taking images at an interval of 60 s. The study found that 37 modules showed 2 hotspots, 15 modules showed 1 hotspot, 12 modules showed 2 hotspots, 9 modules showed 3 hotspots and 1 module showed 4 hotspots. The comparison of the IR image of the panel with one hotspot and four hotspots illustrated that the temperature is lower in 4 hotspots case because of the large area where leakage current is lesser than 1 hotspot case (Fig. 4).

5.4. Lock-in thermography (LIT)

A non-destructive technique, LIT is used to identify failures in crystalline, thin film and organic PV modules. The technology uses an IR sensitive camera, function generator, power amplifier, LEDs for optical excitation and computer for data analysis. Here the excitation of the solar cell is done by injecting a pulse of current either in dark condition (DLIT) or using a light source (ILIT). The presence of local shunts in the solar cell increases its temperature, and the IR camera images the transmitted heat through the cell. Sinha et al. [72] investigated the spatial qualitative and quantitative analysis of optical degradation due to encapsulant discolouration in PV modules (brown and non-brown modules). The authors used DLIT for thermal characterisation using an IR camera by imaging the panels for 100 s at a frame rate of 150 Hz. The study found more temperature variation in brown modules than non-brown modules (Fig. 5). The standard deviation calculation in the acquired pixel data of thermal images revealed that the brown module has a larger electrical mismatch because of the discolouration which results in the reduction of FF and output power. This technique is efficient in finding the power loss due to discolouration effects by imaging temperature difference and defect regions in the encapsulated module.

5.5. Electroluminescence (EL) imaging

The EL imaging is an efficient way to determine the module characteristics as it detects cracks in the cells which appear as dark in the IR image (identified by the CCD camera). The injection of minority carriers to the base of the solar cell results in the emission of photons from the solar cell. These photons are detected by the camera which shows the intrinsic and extrinsic defects that decreases the minority carrier concentration. Sinha et al. [72] used EL imaging apart from DLIT technique to find the extent of discolouration in an encapsulant. The EL images (Fig. 6) showed dark patterns in the centre of brown modules due to EVA discolouration which decreased the transmission of EL radiation from the solar cell. Non-brown modules also showed a dark pattern in some cells which is different from brown panels due to electrical problems like finger breakage. The comparison of EL images with DLIT images confirmed the shaded trend in PV boards. The EL technique also helped in analysing the difference in cell bias voltage in the module by observing the uneven discolouration.

5.6. Ultraviolet (UV) fluorescence imaging

The UV fluorescence of the EVA helps in analysing the yellowing effect of the PV module. The continuous exposure of the EVA to the sunlight results in cracking of molecules inside the lamination foil and thereby results in the formation of chromophores in EVA. Over a period, the presence of oxygen decomposes the fluorescent products to non-fluorescent products through photo-oxidation mechanism. The oxygen later enters inside the cracks and edges of the module which results in degradation. Fluorescence helps in determining the number, position, and orientation of the breaks inside the cells [69]. Muehleisen et al. [52] detected the hail-induced damage of solar cells using UV-fluorescence imaging when the breakage was not visible to the naked eye or recognised with thermography. The authors inspected three hail-affected PV plants located in the south of Austria using digital photographic camera excited with UV-lamp consisting of three tunable power LED arrays and a low pass filter. The cobweb-shaped cracks (Fig. 7) in the solar cell indicated the impact of the hailstones on the panel surface. The authors also noticed strange point shaped extinctions in the UV-fluorescence pattern because of cross-shaped micro cracks in the cells which are confirmed by EL method. Table 7 [5,55,64,71–77] provides a summary of recent research studies on PV failures.

6. Mitigation techniques

The awareness to enhance PV efficiency for improving the energy yield resulted in the development of various mitigation techniques. The environmental factors (described in section 3) such as dust, ambient temperature, wind velocity, humidity, snowfall, hailstorms and sandstorms have a significant impact on PV performance, which could cause panel failure and subsequently results in the degradation of the modules. The following sections highlight the different mitigation methods to reduce the various PV panel degradations.

6.1. Cooling

Cooling the module is an efficient way of improving the

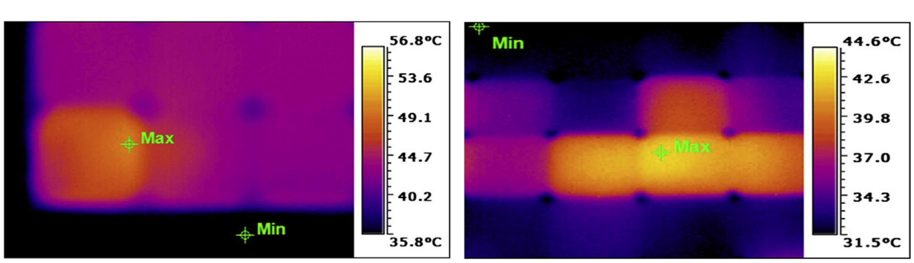

Fig. 4. Infrared image of the module: (a) one hotspot (b) four hotspots (adapted from Ref. [71]).

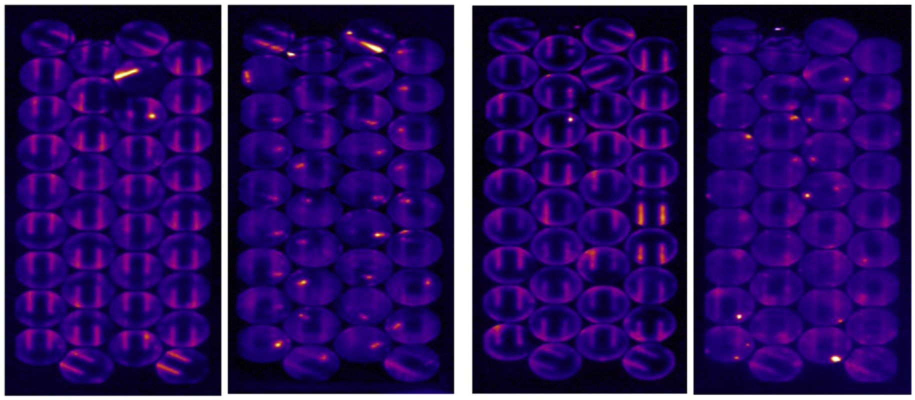

Fig. 5. Electroluminescence images of degraded photovoltaic modules: (a) first module pair (b) second module pair (adapted from Ref. [72]).

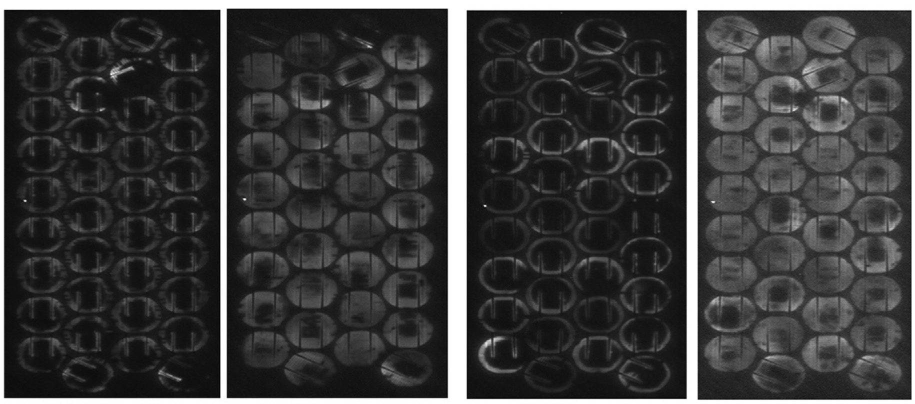

Fig. 6. Dark lock-in thermography images of degraded photovoltaic modules: (a) first module pair (b) second module pair (adapted from Ref. [72]).

performance of PV systems, which depends on the atmospheric temperature, installation of the cooling unit and the material or type of PV cell. In crystalline Si solar cell, a 1 °C rise in temperature reduces the efficiency of the cell by 0.40–0.50% and 0.25% for amorphous silicon solar cells [78]. The following sub-section reviews the literature of two types of cooling the PV panel surface such as active and passive to enhance the efficiency of the solar conversion system. The active cooling (air-active and liquid-active) method requires energy like pump or fan and the passive cooling (air-passive, water-passive and conductive) need conduction or convection to facilitate heat extraction. Table 8 [79–84] summarises the general information and the essential parameters for active and passive cooling techniques of PV.

6.1.1. Active cooling

The active cooling mode is a cost-effective way of reducing the PV module's excessive heating due to outdoor exposure. Nižetić et al. [85] studied the PV performance by water-based cooling techniques to analyse the economic and environmental aspects of a 30 kW PV system operating in the city of Split, Croatia, having a typical Mediterranean climate. A blower fan mounted on a metal stand, and induced airflow stream cools the backside of PV panel using a duct system to focus airflow efficiently. The electricity delivered annually by each 250 W PV

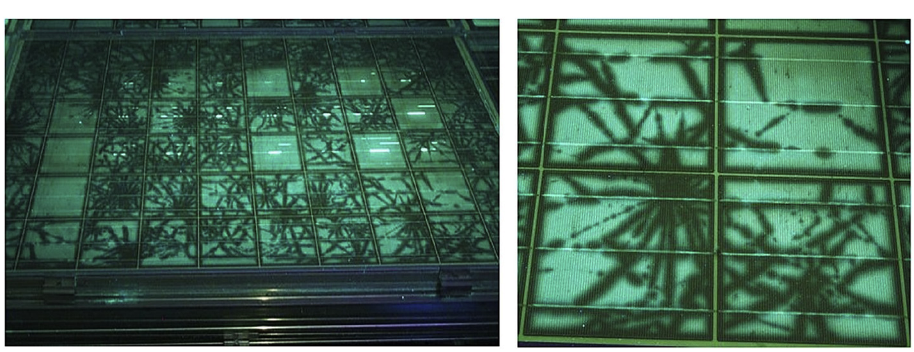

Fig. 7. Hail damaged module of a photovoltaic plant with spider web appearance due to microcracks using the ultraviolet-fluorescence technique (adapted from Ref. [52]).

Table 7

Summary of recently published work on PV degradation process

Country	PV technology	Period	Main flaws	Detection techniques	Reference
India	Crystalline Si	20 years	EVA discolouration, rusted busbar, finger gridlines	Visual Inspection, I-V measurement, Differential current analysis, DLIT, Insulation resistance test	Sinha et al. [72]
Malaysia	p-type poly-crystalline Si	Nine years	Cracks in the module, power loss, leakage current	EL imaging, Dark I-V measurement, Leakage current at high voltage stress, Maximum power measurement	Islam et al. [73]
Algeria	Five mono-crystalline and six poly-crystalline Si	20–25 years	Damaged cell-interconnect busbar, cracks in cells, anti-reflection coating deterioration, degradation of the EVA	Visual inspection, I-V, and P-V measurement	Kahoul et al. [74]
Morocco	Mono-crystalline Si	Two years	Junction box discolouration	Visual inspection, I-V, and P-V measurement	Bouaichi et al. [75]
India	Mono-crystalline Si	25–30 years	Chalking of back-sheet, busbar, cell interconnection ribbon and string interconnection ribbon corrosion, delamination in back-sheet, hotspot, EVA discolouration, corrosion of junction box	Visual inspection, IR thermography, Insulation resistance, I-V characteristics	Rajput et al. [71]
Italy	Crystalline Si	20 years	Yellowing of encapsulant, delamination, front glass defect, busbar corrosion, junction box rust, finger discolouration, cell interconnect ribbon discolouration	Visual Inspection, I-V measurement, EL, Laser beam induced current	Pozza and sample [76]
Algeria	Mono-crystalline Si	More than 12 years	EVA browning, delamination, busbar corrosion, glass breakage, cracked solar cell, solder bond degradation, anti-reflective coating degradation	Visual Inspection, I-V measurement	Bouraiou et al. [77]
India	Mono-crystalline Si	28 years	Delamination, Glass breakage, bubbles on the module back sheet, discolouration of the encapsulant, front grid and antireflective coating oxidation, soiling of junction box, hotspot, cracked solder joints on bus bars	Visual inspection, Thermal imaging, Indoor I-V measurement	Chandel et al. [5]
Algeria	Mono-crystalline and poly-crystalline	Nine months to 32 years	Delamination, discolouration of the encapsulant, corrosion and discolouration of metallization, solar cell cracks, broken glass, deterioration of antireflection coating, snail trails, junction box failure, soiling	Visual inspection, I-V & P-V measurement	Bouraiou et al. [55]
India	Multi-crystalline Si	2.5 years	Snail traits, single cell browning, junction box failure, hotspot, weak string interconnect ribbon	Visual inspection, Thermal imaging, Indoor I-V measurement	Sharma and Chandel [64]

Table 8

The summary of parameters for active and passive cooling techniques

Reference	PV technology	Coolant method	Increase in efficiency	Increase in PV panel power output	Reduction in panel operating temperature	Site/Irradiation level	Experiment conducted
Bai et al. [79]	Si-monocrystalline	Sprinkling and refrigerant	13% on 19/06/2014 and 18% on 22/06/2014 for refrigerant-based	–	–	City of Keszthely, Hungary.	Outdoor
Mazón-Hernández et al. [80]	Si-polycrystalline	Active-air		Up to 15%	15 °C	Spain.	Outdoor
Rajput and Yang [81]	Si-polycrystalline	Passive- heat sink	Heat flux improved by 30% on the rear side of PV panel	–	At front side, 81.7 to 58.4 °C and at the rear side, 88.6 to 47.9 °C	1378.4 W/m^2 using a halogen lamp	Indoor
Hasan et al. [82]	Si-polycrystalline	Passive- PCM	–	–	13 °C on April and 8 °C on June	United Arab Emirates.	Outdoor
Alami [83]	Si-monocrystalline	Passive- evaporative	–	19.1%	85 °C without clay and 45 °C with clay as coolant	University of Sharjah.	Outdoor
Ebaid et al. [84]	Si-monocrystalline	Nanofluids	50%	TiO_2 nanofluid-6.05% Water-3.75%	At 5000 mL/min flow rate, TiO_2-22.90% Water-16.58%	Jerash-Jordan.	Outdoor

panels is about 334 kWh/year, and for an air-induced cooling, the output is 357 kWh/year. The overall investment reached 6300 € when considering the cost of aluminium sheet, metal stand, fan blower and labour cost, to get levelized cost of electricity of 0.097 €/kWh. The economic evaluation of the 30 kW PV system indicated that the air based active cooling is not a viable option as the investment for the technique is very high together with inadequate performance. Cooling the PV front panel surface with water reduced the operating temperature of the PV panel by 20–30 °C. The authors also examined the liquid based cooling technique and estimated a 10–15% performance improvement in active water-based cooling than the air-based cooling (5–10%). The study revealed that the water-based cooling system performed well from a technical point of view and the two active cooling systems are questionable from an economic point of view. The environmental study concluded that the air-based cooling technique suffered the highest ecological impact due to global warming and the acidification effect.

Bai et al. [79] investigated the actual performance of sprinkling and refrigerant based cooling of PV panels installed in the city of Keszthely, Hungary, where the pumping of water takes place from a well after filtering and softening. To reduce the wastage of water and to sprinkle the minimum amount of water required for evaporation on the PV panels, the sprinkler-head operated non-continuously and impulsively. The two samples paired *t*-test, one-way and two-way ANOVA and SPSS 22 performed the statistical analysis. The experimental study revealed that the electrical performance improved by 12% on average even after the usage of 22.5 L water per day on average. The authors concluded that refrigerant based cooling is not a viable option for the climatic conditions of Hungary and suggested that the sprinkling water cooling method is considered better from the aspect of energy efficiency. Sprinkling method exceeded the performance by 19% and 25% (control) and by 13% and 18% (refrigerant-based cooling) on 19 June 2014 and 22 June 2014 respectively.

Mazón-Hernández et al. [80] examined the effects of air channel cross-section, air velocity and panel temperature on the electrical parameters of PV panels installed at the Universidad Politécnica de Cartagena in Spain. The experimental set-up consists of two modules such as panel A (isolated panel) kept in standard conditions used as a reference and panel B (modified panel) held above the steel plate with an air channel beneath the panel. Resistance temperature detectors measured the temperature of the panel and the temperature of air flow inside the channel. The authors evaluated the electricity production for both natural and forced convection and also addressed the relevance of distance between the PV panel and the roof. The study recommended a more prominent space between the PV panel and steel roof for cooling the panel efficiently. In the case of natural convection, panel B is warmer than panel A, and this isolated panel suffered lower panel temperature due to the space beneath the panel. The power production is higher for panel B than panel A for forced convection due to the improvement in heat transferred to airflow. The study also reported that the power output enhanced by 15% and the panel temperature decreased by 15 °C. The authors concluded that PV panel cooling by forced convection is better than the natural convection for the same aspect ratio and irradiance levels.

6.1.2. Passive cooling

Passive cooling techniques supersede the active ones concerning energy savings because the former does not require external power for its operation. The comparison of various passive cooling techniques for PV provides an elaborated analysis of the technical and performance features of the system. Rajput and Yang [81] conducted experimental studies on cooling PV panels passively using a cylindrical heat sink and compared with traditional PV/T collector. The authors used 20 W polycrystalline PV panels and halogen light with an intensity of 1378.4 Wm^{-2} to enhance the indoor temperature. The circular pin fin heat sink, having fin density 1.22 fin cm^{-2} lowered the temperatures to

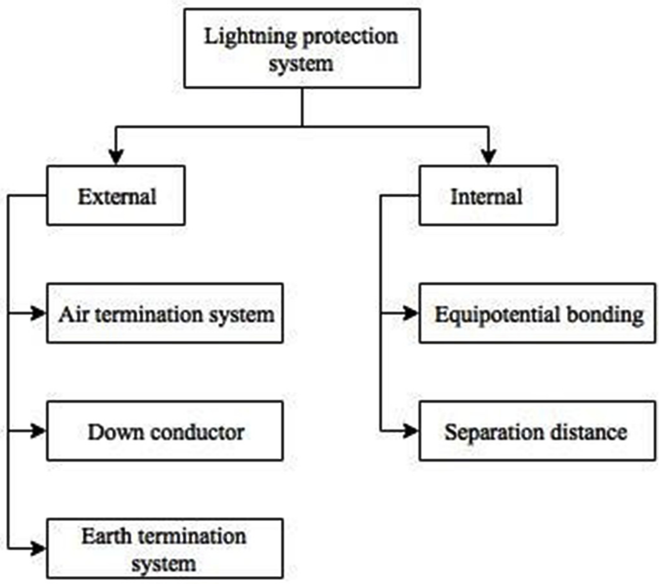

Fig. 8. Classification of various lightning systems (adapted from Ref. [87]).

81.7 ± 2.3 °C and 88.6 °C at the front side and rear side respectively. The study found that the heat sink reduced the temperature to 58.4 °C and the collector temperature to 47.9 °C. The natural methods enhanced the heat flux (667.2 Wm^{-2}) at the rare side of the panel by 30% using the heat sink and by 41.5% using PV/T collector. The authors also suggested for future work to conduct the experimental study using the heat sink to cool the panel under stagnant wind conditions.

Abd-Elhady et al. [86] suggested a natural convection method using holes to prevent the overheating of PV panels due to the radiation emitted by the Sun and conducted experiments and numerical simulations in Cairo, Egypt on 22nd of July 2016 to examine the influence of hole size and the number of holes in PV panels. The authors conducted experiments on two identical 25 W mono-crystalline PV panels with one panel perforated with 9 through holes, and the other, non-perforated with no gaps. The exposure of PV panels to ambient temperature resulted in a temperature difference between the two modules causing a higher temperature for non-perforated panel than the perforated panel by 8 °C along the day. The comparison of experimental results with the numerical model assisted in selecting the hole size and number of holes for cooling the panel. The study concluded that the holes in the PV panels decreased the surface temperature and helped in cooling the panels. An increase in the number of holes resulted in the reduction in temperature, which becomes marginal after a definite number of holes. The authors also recommended a critical diameter of the holes to allow the hot layer of air to pass through these holes for effective cooling. Hasan et al. [82] monitored the cooling effect of the PV panel using paraffin based PCM in the hot environment of the UAE. The experimental methodology involves the calculation of temperature at the PV front panel with and without PCM. The authors also developed a model to predict the PCM melt and solidification fractions in every month to indicate the progress of solidification. Containers consisting of PCM as the liquid (10.2 L) is attached to the PV and subjected to cooling before crystallisation. The developed model helped in identifying the variation in PCM cooling performance in different months. The warmer ambient temperature solidified the PCM in summer, and it couldn't melt during winter due to lack of thermal energy. In April and October, the intense solar radiation dissolves the PCM thoroughly, and it solidifies during night time due to lower ambient temperature. The study concluded that the presence of PCM reduced the PV temperature by 10.5 °C on an average during peak time causing a 5.9% enhancement in PV output power annually.

Alami [83] devised a low-cost cooling method using copper covered in synthetic clay as a passive evaporative material for testing 10 W identical monocrystalline PV panels. The commercially available perforated copper substrate with 6 mm array of holes provided the cooling effect, which was kept between two layers of Kera clay. The authors conducted characteristics test on two identical PV modules installed outside the heat transfer lab of the University of Sharjah during solar noon in the last week of July 2013. The study found that the temperature of the PV module with and without clay reached 45 °C and 85 °C respectively. The authors concluded that cooling the modules with clay enhanced the output voltage by 19.4% than the modules cooled without clay (19.1%).

Ebaid et al. [84] experimentally investigated the cooling of 50 W mono-crystalline PV panels using two nanofluids for a volume flow rate of 500–5000 mL/min at 0.01–0.1 wt% in the climatic conditions of Jerash-Jordan. A heat exchanger made of aluminium kept at the back surface of the PV panel provided cooling using nanofluids such as Al_2O_3 in water-polyethylene glycol mixture at pH 5.7 and TiO_2 in water-cetyl trimethyl ammonium bromide mixture at pH 9.7. Heat sink ensured good contact between the heat exchanger and the PV back surface. Ultrasonic vibration breaks the sedimentation of nanoparticles, and the addition of surfactants reduced the surface tension of the liquids. The study revealed that the increase in nanoparticle weight fraction and flow rate minimised the PV cell surface temperature. Al_2O_3 nanofluid provided a better reduction in PV surface temperature when compared to TiO_2 nanofluid. The authors also found that the power and the efficiency of the PV cell enhanced with flow rate and concentration of the nanoparticles.

6.2. Lightning protection

Protecting the PV module from lightning is essential and necessary to avoid the faults and damages in auxiliary equipment attached to the installation. Lightning results in a direct strike, over voltage and heat treatment of the PV modules, thereby degrading the electrical characteristics and deteriorating the output voltage to zero. This efficiency reduction of the PV module forces the PV users to design and accommodate lightning protection system in the PV site based on the latitude, installation and usage. Ahmad et al. [87] illustrated the classification and the explanation of the various lightning protection systems for the PV plants (Fig. 8). Kokkinos et al. [88], addressed the different concerns to configure a universal structure for the lightning protection system layout of PV installations. The authors conducted experiments at ELEMKO'S H.V lab in Greece and offered possible solutions to overcome the various challenges which could arise at the site of PV installations. The PV park included 7300 solar panels of 270 W nominal power, 180 DC/AC inverters of 11 kW power mounted on concrete reinforced bases embedded in the soil. The authors considered isolated and non-isolated application design for the lightning protection system. Based on the foundation of the PV framework, the study suggested various materials for the earthing system driven into the soil. The study recommended a minimum distance of 3 m between the PV frame of each row and the earth electrode. As conducting experiments in PV park is difficult, the authors performed a scaled-down analysis using 2 MW PV system consisting of 9 PV modules in series giving 200 V output voltage and 10 A current. The authors tested the two possible cases to check for lower induced voltage without any illumination at the DC cable loop. The results revealed that the non-isolated protection system provided lower induced voltage in case of the lightning strike and considered as a cost-effective option when compared to remote lightning design. Hence, the authors preferred to use non-isolated light protection system for the PV park.

Ittarat et al. [89] developed a computer program to decide whether there is a necessity to install a lightning protection system in PV or not. The authors collected data from a 25 kW PV system installed at Thayang district, in the Phetburi province of Thailand. The evaluation of damage from lightning included the assessment of the frequency of N_c and the frequency of N_d of the PV systems. The authors used the visual basic program and applied protection angle technique to identify the height and number of lightning rods required to install the rods behind the PV panel and thereby ensured the PV components in the protection zone. The program calculated the value of N_c and N_d as 10×10^{-6} and 9.945×10^{-3} which suggested for the necessity of a lightning protection system. The protection angle method validated the program result with the 3D drawing program and identified that the PV panels are in the protection zone. Using the program, the authors recommended installing the lightning rod with a height of 12 m for five poles, each with the protection of 58° and a radius of 19.20 m.

Proper installation of the PV panels and the accurate design of the lightning protection system enhances the efficiency of the power generation with the least lightning hazards. Construction of the PV installation site and the design of the lightning system must take place simultaneously to improvise the efficiency of the protection system. The lifespan of PV operation improves when the corrective protective techniques satisfy the standard requirement of PV installation.

6.3. Dust removal

The exposure of the PV panels to various weather conditions result in the deposit of a layer on the panel surface due to dust, dirt, atmospheric pollution, algae, bird droppings, etc., which is more difficult to clean if left unattended for a long time. Accumulation of dirt and soiling on the PV panel surface degrades the system performance. This concern resulted in the classification of various methods for soiling and dust mitigation (Fig. 9) to increase the efficiency and reliability of the PV systems [90].

6.3.1. Manual cleaning

Manual cleaning is the traditional way of reinstating PV panel surface to cleaner condition as the method wipes out hard soiling like bird droppings and cement dust from the panel efficiently by human resources. However, the labour type of cleaning is highly costly for large-scale PV plants. The tools required for dusting, water, detergent, labour charge, safety and welfare of the workers, add extra expenditure to the process. Manual cleaning also causes physical damage to the PV panel surface such as abrasions and cracks on the cells, which can be avoided by using brushes with soft bristles and soft cleaning clothes. Manual cleaning is not safe for PV-plants installed at elevated heights and for offshore solar plants. Alnaser [91] investigated the effect of human-made cleaning of PV panels on the performance of the Sadeem BIPV building at BAPCO, Awali, Kingdom of Bahrain. The 36 PV panels installed on the rooftop required 500 L of distilled water every two months for cleaning. The author collected the PV data three days prior and also after cleaning the panels to analyse the amount of loss in the power yield due to dust accumulation. The study revealed that the human-made cleaning once in two months raised the PV panel efficiency by 6%. The author also noted that cleaning of 160 rooftop PV panels in MBRSC in Dubai, the United Arab Emirates once in a month improved the energy yield by 8% when the average global solar radiation is 450 W/m^2.

6.3.2. Natural cleaning

Natural cleaning by rainwater is suitable for locations where precipitation is plenty and for PV modules that are fixed at a larger tilt angle. This method cleans only loose dust on the panel surface leaving behind the dirt that is stuck on the panels due to moisture. Despite the improvement in power output from PV modules with rainfall, relying on precipitation for cleaning is not advisable as it happens only occasionally and less in dry regions. Alnaser et al. [92] compared the performance of human-made and naturally cleansed 2088 solar panels at University of Bahrain by selecting eight PV panels for manual cleaning with distilled water and another set consisting of seven PV panels left without cleaning. The study found that the solar electricity produced by PV panel (left for natural cleaning) is 5.9% more than the data predicted by the developer (PetraSolar) and is 15.3% less than the literature value. This data comparison revealed that the PV panels left for the natural mode of cleaning produced low solar power of 9% than the PV panels cleaned by labour. Wind also reduced the deposition of dust on the module surface as the direction and wind speed profoundly influenced the performances of the PV module [93]. Jiang et al. [94] developed a model using particle resuspension theory to analyse the wind cleaning method of dust particles from the flat PV module surfaces. The authors evaluated the minimum shear velocity (0.23–57.56 m/s) and actual wind velocity (0.82–2219.8 m/s) which re-suspends the dust particles from the PV module surface. The study suggested that it is necessary to convert the direction and speed of airflow into actual velocity along the path of PV modules, to predict the wind cleaning process for PV modules. This model is suitable for flat surfaces as the relation between free stream velocity and actual velocity on the inclined flat is uncertain. The work suggested further advanced research on the influence of inclined angles on cleaning to expose the importance of installed location.

6.3.3. Hydrophobic surface

Hydrophobic surface removes soiling from the PV panel surface with natural precipitation or water cleaning system. This coating enhances the solar absorption capability of the panel by increasing the active area to trap the sunlight. The chemical coating increases the degradation of PV panels due to UV exposure, and a weatherproof coating reduces this risk. Fathi et al. [95] investigated the performance of nanocoating PV panels cost-effectively. The procedure of surface modification involved cleaning with nanotol primer solution, drying with microfiber weeper and spraying using nanotol sealant solution. The authors conducted I-V measurement using a data acquisition system to test the electrical parameters match to standard test conditions. The PV modules with and without hydrophobic coating underwent hydrophobicity and optical test and compared the dust and water droplet deposition on the PV modules. The experimental study found an enhancement in light transmission and open-circuit voltage in nanocoated PV panels. The thermal study explained that the dust particles created a shadow effect on the panel surface (non-coated) and created a hotspot that increased the panel temperature and decreased the open circuit voltage. Hence the nanocoated PV panel with self-cleaning nanomaterial performed better in the hot climate of MENA regions. The nanocoating proposal is a cost-efficient cleaning method as the

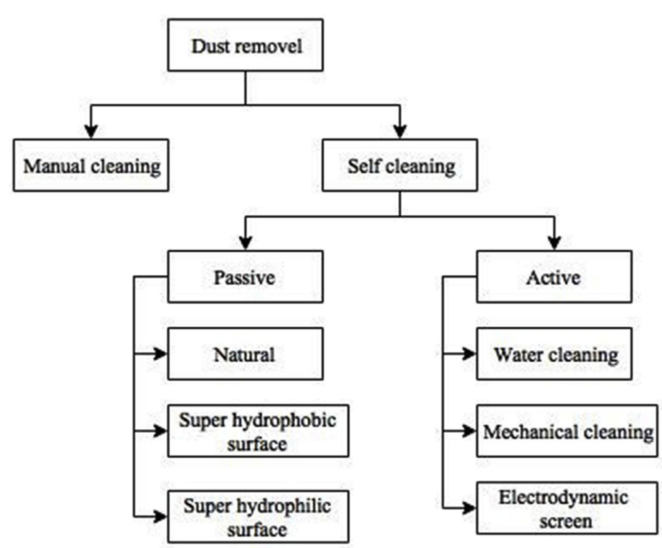

Fig. 9. Various methods to mitigate soling from photovoltaic plants (adapted from Ref. [90]).

technology cost about 1.89 Euros/m^2/year which is equivalent to 18.900 Euros/1 MW/year.

6.3.4. Hydrophilic surface

Hydrophilic surface uses a chemical coating or screen layer for removing soiling, where the surface has a strong tendency to attract water. In this self-cleaning mechanism, the water droplet spreads on the surface, moves deep inside the dust particle and carries it away. Zhong et al. [96] designed a novel super-hydrophilic coating consisting of 3-triethoxysilylpropylamine and TiO_2 (which act as a photocatalyst) on the surface of the PV panel. The pulling method loaded the substrates on the glass sheets after cleaning the modules with cleaning compounds. SEM analysed the particle size distribution and surface structure, whereas XRD and TEM investigated the TiO_2 nanocrystal. The lower static water contact angle of 5° exhibited the superior hydrophilic property of the chemical coating. The study found that the power generation from the treated panels was higher than the untreated ones to a maximum of 4.2%.

6.3.5. Water-based cleaning

Cleaning using water is another relevant method to ward off solid particles stuck on the PV surface. Analogous to natural cleaning methods, the water-based cleaning lacks in reliability due to the enormous amount of water and power required, fear of water clogging and thermal shock in PV panels and accumulation of chemical deposition. Moharram et al. [97] used surfactants and water to remove the dust deposited on the 14- kW PV power plant installed in the German University in Cairo, Egypt. The authors conducted a study to clean the panels using a non-pressurized water system with less amount of water and energy daily for 10 min for 45 consecutive days at a flow rate of 12 L/min. The investigation included analysing the performance of the panels without cleaning, cleaning using non-pressurized water and cleaning using water and surfactant. The study revealed that the efficiency of the PV panels reduced by 0.14%/day and by 50% while cleaning with non-pressurized water and after 45 days of cleansing with water alone respectively. The experiment found the usage of surfactant reduced the quantity of water required for cleaning and the mixture of anionic and cationic surfactants minimised the dust particles deposited on the panel and hence maintained the efficiency of the plant.

6.3.6. Mechanical methods

Cleaning the PV panels includes a lot of mechanical systems in different designs depending on the location, choices and the purpose of the PV systems. These cleaning methods consist of automatic wipers, blowers, removable covers, brushes and storage tank with sprinklers that get activated mechanically or electrically based on dirt detection. Shehri et al. [98] designed a testbed and studied the impact of brush-based dry cleaning on PV panels. A sand deposition shaking system continuously deposited dust on the brushed surfaces to create a real environment equivalent to 20 years. The cleaning tools included nylon, cloth, and silicon rubber foam for brushing anti-reflective coated solar panels. The study of the brushing effect revealed that the solar panels cleaned with silicone rubber brush enhanced the power output of 1% on an average from the unbrushed initial output power. SEM analysis of the PV sample suggested that the nylon brushing caused large scratches which in turn affected the coating surface. The qualitative comparison of cleaning the panels with three brushes confirmed that the cleaning tools such as nylon and rubber cleared the humid dust layers when compared to cloth cleaning.

6.3.7. Electrodynamic screen (EDS)

The development of EDS used the concept of dust's electrostatic property to mitigate the adverse effect of soiling on solar panels. This dust removal technology uses high voltage supplies to power the electrodes of a transparent screen which in turn helps in expelling the charged and uncharged dust particles from the PV panel surface. Kawamoto and Guo [99] developed an electrostatic cleaning system to remove dust from the surface of the solar panel using electrostatic forces. The prototype included dust cleaning plates with parallel wire electrodes embedded in the borosilicate glass substrate and a high voltage source to generate the two-phase high voltage. The study suggested that operating the cleaning system together with natural wind improved the performance for initial bulk loading of dust. An anti-dust insulative coating on the panel enhanced the cleansing due to lower surface voltage. The work suggested for field experiment for a longer duration of time to exhibit the effectiveness of the system.

7. Conclusion and future direction

Deriving power from solar energy is an essential application in the renewable energy sector as it is eco-friendly and sustainable. This paper reports the environmental factors hampering the various components of the photovoltaic systems. The work reviews the significant environmental conditions affecting the performance of the photovoltaic systems. The review also provides a comprehensive outlook about the various failure modes, failure detection methods and different mitigation techniques to reduce the performance degradation. Researchers working on PV modules can experiment on the concurrent effect of these parameters on PV performance in their future R&D (research and development) work. The co-relations developed based on these experiments helps the policymakers and the investors to adopt precautionary measures for reliable operation.

In summary, the following recommendations are made:

- Forecasting the environmental parameters like dust, temperature, wind turbulence, humidity, snowfall, hail and sandstorms helps the investors to make an alternate arrangement for protecting the solar plants. The specification sheet of the PV panels, associated power-conditioning equipment provides an estimated knowledge of the performance based on ambient conditions. Preparation of the database of environmental and climatic conditions like wind velocity, precipitation, relative humidity, temperature and other factors suitable to the site of PV plant is essential.
- Panels must be tested to withstand the harsh environmental factors. Manufacturers must test and certify the resilience of the solar panels against extreme climatic conditions. The expert installation of the PV modules ensures a long life of the entire system by overcoming the adverse weather factors. The solar panel technologies and the attached auxiliary components of the PV plant must fulfil the requirement of the installed site.
- Periodic maintenance of the solar panels by signing production warranty, installation and solar equipment warranty from the installer is necessary for the smooth working of the PV systems. Insuring the solar panels or the energy system against adverse climatic conditions, theft and damage from the animals would attract more buyers.
- Modelling of the solar plants helps in investigating standard steady-state analysis together with time-dependent dynamic analysis. This modelling helps the operators in predicting the function of renewable sources based power plants with forecasted meteorological conditions. Modelling plays a critical role in the initial stages of plant development, and to assist the investors to make better decisions. An accurate methodology to establish the performance of the PV plant provides a reliable database for prediction and validation of the energy yield.
- In future, research needs to be carried out on how to dispose and recycle the failed PV modules affected due to environmental factors. The government must encourage organisations to involve in solar panel recycling process with economic incentives.
- New R&D, technology transfer and vibrant approaches among equipment manufacturers, investors, customers and other bodies strengthens the consciousness of investment in the solar industry.

Further advancement in technologies that enhances the efficiency and reduces the degradation processes of the solar panels are the areas of future research to increase the energy yield from the PV systems.

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