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The Effects of Dust and Heat on Photovoltaic Modules: Impacts and Solutions

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Preface

Solar energy is abundant and the harvesting technology is quite mature. Most solar panels can generate energy even on cloudy days. As a result, solar power is suitable for most countries with varying climates. Growing photovoltaics deployment around the world is increasing the renewable energy percentage share within the global energy mix. Gulf Cooperation Council (GCC) region and many other parts of the world, where the sun shines very high on most days of the year, the PV-based energy generation and utilization has huge prospects. However, in those parts of the world, PV modules suffer from two major challenges; the first one is the high temperature during the summer and the second one is the dust, which is nearly throughout the year. The current market leader, the crystalline silicon (c-Si) PV module, has efficiencies ranging from 15–23% after testing at 25 °C in a laboratory condition. The efficiency of some cells, multi-junction, and concentrated solar cells can even reach above 40 %. The materials used in the PV modules, i.e., silicon and metal, are good conductors of heat. All materials including the polymeric encapsulant lose durability after extended exposure to the sun, due to the heat and UV radiation, reducing the efficacy of the unit. The PV installation, especially in the case of the commercial electricity generation purpose, requires significant investment, and in the end, the company needs to make a profit. Most of the bright parts of the world, where the sun shines very high on most days of the year and solar radiation is also high, is somehow close to desert areas. Therefore, the accumulation of dust particles on PV surfaces is a major concern. This does not only affect the power conversion efficiency but also fuels the module temperature rise by the shading effect. Dust particles are of different sizes and properties, deposition varies with the season and weather conditions. So, dust deposition can affect the PV module by particle shading, which can create hotspots and can create soiling, which depends on the dust deposition uniformity, partial size, and density. However, all these can significantly affect PV power conversion efficiency. Even it was also observed that the sand storm in the Sahara Desert (February and other in March 2017) impacted PVs in Portugal (Southern Portugal, Évora, and Alter do Chão) (*Ref.Sol. Energy 160 (2018) 94–102*). Again, the cleaning process brings extra cost and can also affect the long-term transparency of the top PV layer.

On the other hand, c-Si solar cells' power conversion efficiency has a direct relation with the module temperature. As per the standard test conditions of commonly used c-Si-based PV modules, the best efficiency obtained was around 25 °C. However, during the summer season, the PV module temperature can reach over 70 °C in desert areas, where the solar radiation is high. Rising cell temperature creates localized hotspots and drastically reduces V_{oc} of the cell and hence, degrades the module efficiency and life. It was reported that the efficiency reduces by ~0.3 to 0.5% for each degree rise of the temperature above the optimum temperature (*Ref. Case Studies in Thermal Engineering 21 (2020) 100674*).

In both cases, the efficiency loss is significant, in terms of power generation and monetary loss. Therefore, there is a serious effort from both academic and industrial organizations to address these two important hurdles affecting the PV-based renewable electricity generation in the brightest part of the world, where solar radiation is high and has dust issue as well. Citing the importance of these two issues, we tried to compile this book to present the current status of research in these areas along with the future possibilities under one roof. We hope the researcher will find this book informative and useful for their ongoing research work.

Seven high-quality chapters addressing the dust properties, cleaning approaches, PV surface coating, and texturing are presented in the first part of the book. In the second section, seven high-quality chapters are arranged to address the effect of the temperature on PV modules, different cooling approaches, and also the effect of the environment on the incoming PV technology.

We believe this book will be useful for researchers, undergraduate, and graduate students working on dust and temperature-related issues on the PV modules in the high-temperature region of the world.

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Contents

Heat

Dust

Dust Deposition on Photovoltaic Modules: Its Effects on Performance

Damasen Ikwaba Paul

Abstract The electrical energy generated by photovoltaic (PV) modules depends on solar radiation, environmental and climatic factors as well as inherited system and component performances. However, the other external factor such as dust also has significant effects on the performance. This chapter discusses the deposition of dust particles on the PV module surfaces and their effects on system performance. The chapter begins by discussing the fundamentals of a PV module and dust particles originality, transportation and the factors that govern their deposition. Results show that the accumulation of dust particles on PV module surfaces is influenced by dust particles properties (size, shape and chemical properties), environmental conditions (wind speed, location and distance to the dust source, dust concentration and weather condition) and PV module characteristics (tilt angle, orientation and properties of surface material). On the other hand, the presence of dust particles on PV module surfaces reduces significantly the transmitted incident light to the solar cells which in turn decreases the value of the short-circuit current (I_{SC}), maximum power output ($P_{\max}$), fill factor (FF), conversion efficiency (η) and energy yield. The rate of decrease of each parameter increases as the dust particles deposition density increases. In addition, the reduction in I_{SC}, $P_{\max}$, FF, η and energy yield depends on the physical properties of dust particles such as mean diameter, size distribution and chemical composition. The effect of dust on the performance of PV modules can be eliminated by cleaning the dust particles using different methods. These methods are classified as natural, manual and automatic.

Keywords Dust particle · Dust particle deposition · Effect of dust on PV module parameters

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1 Introduction

Solar energy is the radiant light and heat emitted by the sun. It is available on the earth's surface in the form of solar radiation [1, 2]. When solar radiation falls on the solar cells, also known as photovoltaic (PV) cells, it is converted directly into electrical energy and/or indirectly into thermal energy [3, 4]. The majority of PV modules are at present used for power generation and in various applications in buildings, transportation, communication systems, stand-alone devices, agriculture, medical refrigeration and streetlights [5]. The most important advantages of using PV modules over the traditional energy sources include renewability, reduction of greenhouse emission gases and increasing security of energy supply [2, 6]. However, the effectiveness of PV modules depends on various factors such as solar irradiance, cell temperature, wind speed, dust particles deposition, shading and solar cell materials [7].

This chapter presents the discussions on the dust deposition on PV modules and its effects on system performance. The chapter is organized into six sections, including this section which highlights the applications and advantages of solar electricity. Section 2 focuses on the fundamentals of the PV module, which include components, technologies, classifications and factors that affect the performance of PV modules. Section 3 is an in-depth discussion on the sources, transportation and deposition of dust particles. The analysis of the effects of dust on various PV module parameters (short-circuit current, open-circuit voltage, maximum power, current against voltage curve, fill factor, conversion efficiency and energy yield) is presented in Sect. 4. Section 5 presents the descriptions of mechanisms used to remove dust particles from the surface of the PV modules while conclusions and recommendations are presented in Sect. 6.

2 Fundamentals of Photovoltaic Module

2.1 Components of a Photovoltaic Module

A solar cell is a device that converts solar radiation into electrical energy through a process called the photovoltaic effect [3, 4, 8]. Although the photovoltaic effect has been observed in a junction of two dissimilar metals, the primary materials used for PV cells are semiconductors [9]. This is due to the fact that semiconductor materials have both electron mobility and gaps between electron energy states that are compulsory for current and voltage generation [10]. When sunlight shines on the surface of the PV cell, a fraction of the photons is reflected from the surface and the remaining photons are absorbed into the cell or transmitted through the cell [8]. Photons that are reflected by the top connecting tabs of the cell and those transmitted through the cell form part of the optical losses of the PV cell. A key factor that determines if a photon is absorbed or transmitted through the PV cell is the energy of the photon at a particular wavelength, $E_p(\lambda)$, given by Eq. 1 [8]. For a photon to be absorbed, its energy (E_p) must be greater than the semiconductor bandgap energy, E_g (i.e., $E_p > E_g$). Thus, photons with energy less than the bandgap of the PV cell pass through it as if it were transparent because they cannot create an electron–hole pair. Another factor that determines the absorption of photons in the PV cell is the thickness of the solar cell [8]. Solar cells such as multi-junction (which consist of different layers of material) absorb more photons than single-layer solar cells.

$$E_p(\lambda) = h\upsilon = \frac{hc}{\lambda} \tag{1}$$

where h is Planck's constant, c is the speed of light, υ is the frequency of the photon and λ is the wavelength of the light.

The electrical energy output of a single PV cell depends on the design of the cell and the semiconductor(s) used, but it is usually insufficient for most applications. To achieve the necessary levels of current and voltage, a number of solar cells are electrically connected either in series or in parallel to form a PV module or array as shown in Fig. 1. In principle, when solar cells are connected in series, the total current of the PV module is the same as the current generated from the least productive cell, whereas the total voltage is the sum of the voltages produced by each solar cell [11, 12]. On the other hand, when the PV module is formed by solar cells in a parallel connection, the total current is the sum of the currents produced by each cell while the total voltage is the same as the voltage of the single solar cell [11, 12].

Currently, most of the PV modules in the markets consist of six main components, namely aluminium frame around the outer edge, top surface cover usually tempered glass (3–4 mm thick), solar cells, encapsulation–ethyl vinyl acetate (EVA) film layers, polymer rear back sheet and junction box [11, 14, 15]. The arrangement of these materials in the construction of the PV module is shown in Fig. 2 and the main function of each component is presented in Table 1.

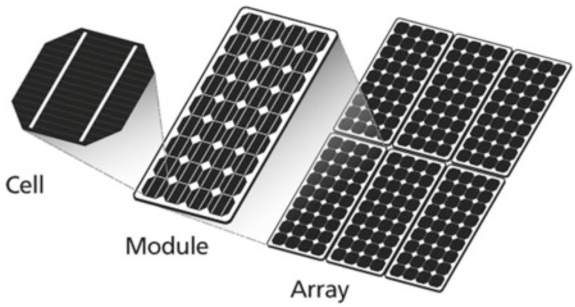

Fig. 1 Photovoltaic terminologies (Reproduced from [13]) [Permission to reuse granted from [13]]

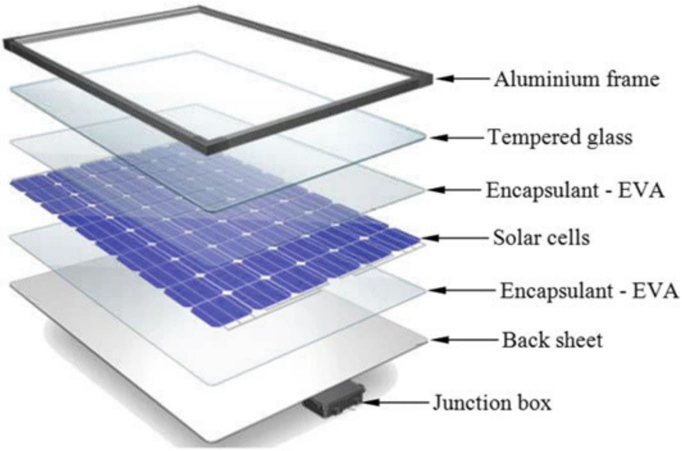

Fig. 2 Schematic view of PV module components (Reproduced from [14]) [Permission to reuse granted from Clean Energy Reviews]

Table 1 The main function of each component in the PV module [11, 14]

Name of the material	Main function
Aluminium frame	Provides the structural stability for the overall combination of glass, encapsulant-EVA, solar cells and back sheet
Tempered glass	Provides mechanical strength and protects the solar cells from physical damage as well as extreme temperature changes
Solar cells	Convert sunlight directly into direct current (DC) electrical energy
Encapsulation–EVA	Provides adhesion between the solar cells, the top surface and the rear surface of the PV module. It also prevents moisture and dirt ingress into the solar cells
Polymer rear back sheet	Prevents the entrance of water or water vapour to the solar cells and provides both mechanical protection and electrical insulation
Junction box	Protects the electrical connections of the solar cells from environmental conditions such as moisture and dirt

2.1.1 Types of Photovoltaic Modules

Photovoltaic modules are given names depending on the materials used to fabricate the solar cells. Generally, solar cells are categorized into three technologies, namely first, second and third generations which depend on the materials used and the level of maturity of the technology [16]. The first-generation technology consists of single-crystalline silicon (c-Si), multi-crystalline silicon (mc-Si) and gallium arsenide (GaAs) solar cells [16] that are relatively expensive to produce and have low conversion efficiencies in the range of 18.4–26.7% [17]. To date, monocrystalline and polycrystalline silicon PV modules are the most common and account for approximately 93% of all modules sold globally [18]. On the other hand, second-generation PV cells were introduced to reduce the cost of production due to the fact that they are fabricated using low-cost supporting materials such as glass or plastic [19]. These cells are single-junction thin-film that uses less material but have lower efficiency than the first-generation PV technology. The second-generation PV cells include amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium di-selenide [Cu(InGa)Se_2 or CIGS] [16, 20]. Currently, a-Si-based PV modules which typically exhibit stabilized conversion efficiencies in the range of 9–14% [21] accounts for approximately 4.2% of the world market sales [18]. In contrast, third-generation PV cell technology is a range of novel alternatives to first and second-generation PV cells. Research and development in third-generation PV cells aims at achieving high efficiency at low cost. The third-generation PV technology is concerned with exceeding the theoretical Shockley-Queisser efficiency limits and include nanocrystal, multi-junction, polymer, dye-sensitized and concentration-based PV cells [20, 16].

2.2 Classification of Photovoltaic Modules

Regardless of the materials used to fabricate the solar cells, PV modules can be classified as flat PV modules or concentrated PV (CPV) modules, i.e., solar cells with concentrators [22]. Contrary to standard flat PV modules, CPV modules use lenses or mirrors to collect sunlight rays from a large area and bend the rays onto a smaller solar cell area [23–25]. As a result, the solar cell area required for producing a given amount of power is reduced.

3 Factors Affecting the Performance of Photovoltaic Modules

The operation and efficiency of PV modules depend on various factors such as environmental, PV module system, installation and miscellaneous. Environmental factors include solar irradiance, cell temperature, wind speed, dust accumulation and shading [26–31], whereas PV module internal factors include the types of solar cell materials, inverter efficiency and battery efficiency [27, 28, 30]. On the other hand, installation factors are related to PV module orientation and tilt angle, the power dissipated in the connecting wires and mismatch losses [28]. The other important but miscellaneous factors that affect the output of the PV module include degradation in PV modules, parasitic resistances and sizing of the PV modules during installation [28, 30]. Nevertheless, the maximum power output of the PV module is a complex parameter that is influenced by a lot of other factors as illustrated in Fig. 3 [7]. This chapter discusses only the effects of dust deposition on the output parameters of the

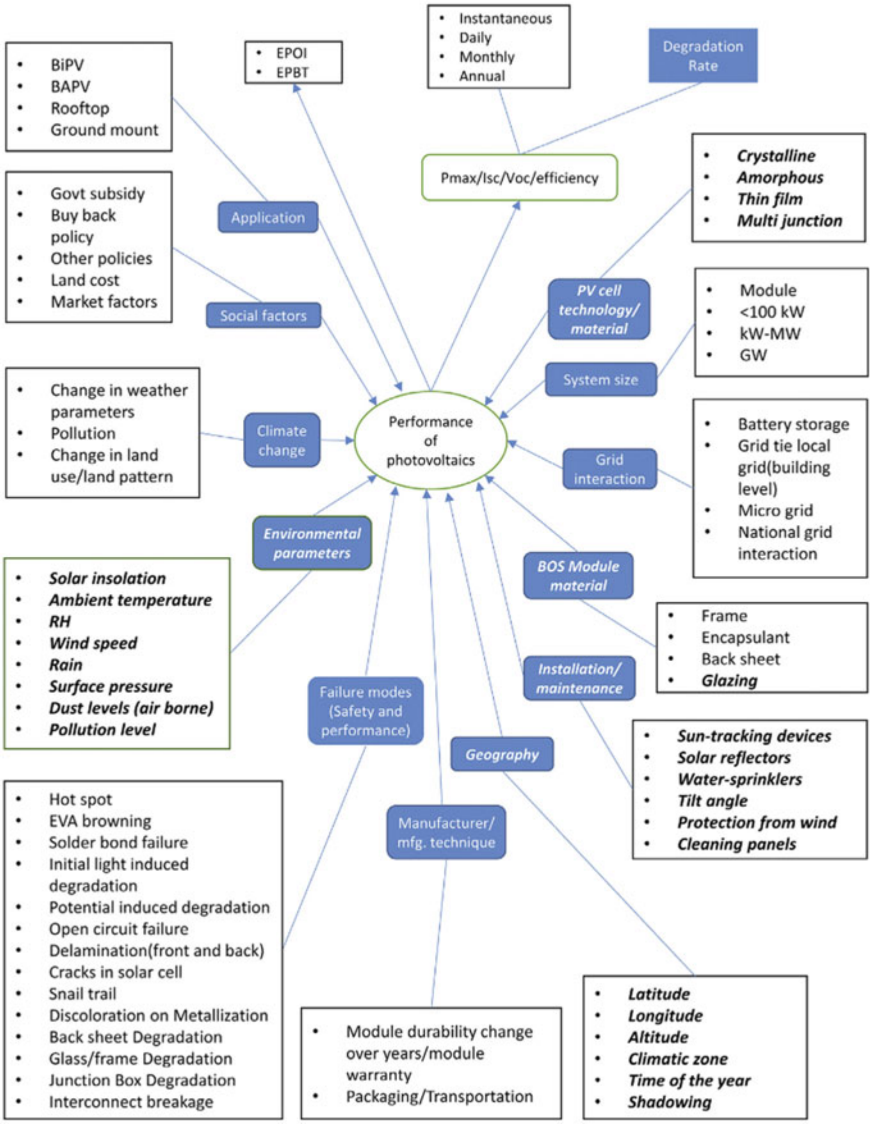

Fig. 3 Factors affecting the PV module yield (Reproduced from [7])

PV module which include short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), maximum power output (P_{max}), current against voltage (I–V) curve, fill factor (FF), conversion efficiency (η) and energy yield.

4 Sources, Transportation and Deposition of Dust

4.1 Sources and Characteristics of Dust

Dust particles are dry solid matter in the form of small irregular particles, many of which are microscopic in size projected into the atmosphere by natural forces such as wind and volcanic eruption or man-made processes such as crushing, grinding, milling, drilling, demolition, digging, conveying, screening, bagging and sweeping [32]. Dust originates from natural processes such as erosion of soil, sand and rock, volcanic eruption, pollens and sea spray or from human activities such as waste incineration, mineral and material processing, industrial activities and road transport [33–36]. The majority of dust sources in the world are located in the Northern Hemisphere, commonly known as '*dust belt*' [37, 38]. These areas include the West Coast of Africa, the Middle East, Mongolia, China, Iran, Afghanistan and Pakistan [39]. However, the chief producers of dust within these regions comprise the Sahara desert, the Namib and Kalahari deserts, the Gobi desert, the Taklimakan desert, Middle East, Southwest and Central Asia as well as Arabian Peninsula [37, 39]. Other minor sources of dust include the Great Basins in the Western United States, Mexico, Central Australia, Southern Africa and Bolivia [37].

Dust particles vary in size, shape and composition due to different mechanisms and geographical locations. However, the diameter of most dust particles in the atmosphere is less than 500 μm [33, 35]. The size of dust particles is significant to the accumulation of dust on the surface of the PV module as it determines their dynamic properties in the air and hence the distance travelled before deposition. This is due to the fact that the smaller the particle, the longer it stays in the air and the further it can travel. On the other hand, the chemical composition of dust particles varies widely with the nature of the dust source as shown in Table 2 [36].

4.2 Dust Particles Transportation

Dust particles of different size adopt different modes of movement from their emission source to the point of deposition. These include saltation, creeping and suspension as illustrated in Fig. 4 [40]. The distance at which dust particles travel in the atmosphere from the emission source depends mainly on wind speed and particle size [37, 38, 40]. When the velocity of the wind is sufficient enough, the dust particles with diameters between 70 and 500 μm are lifted and hop along the surface in the wind direction in a process commonly known as saltation [37, 40]. However, due to large inertia, dust particles with diameters greater than 500 μm do not saltate but fall back after a short hop or creep along the surface (Fig. 4). On the other hand, dust particles with diameters between 20 and 70 μm are suspended in the air for a short period of time (i.e., short-term suspension) because of their small terminal velocities. These particles travel few kilometres before being deposited unless the weather situation

Table 2 Composition of dust particles from different sources [36]

Source of dust	Elements[1] emitted
Road transport	
Motor vehicle emissions	Br, Pb, Ba, Mn, Cl, Zn, V, Ni, Se, Sb, As
Engine wear	Fe, Al
Tyre wear	ZnO, Carbon black
Road-side dusts	Al, Si, K, Ca, Ti, Fe, and Zn
Industrial activities	
Oil-fired power plants	V, Ni
Coal combustion	Se, As, Cr, Co, Cu, Al, S, P, Ga
Oil refineries	V
Non-ferrous metal smelters	As, Sb, Cu, Zn, Pb, Cd, Hg
Iron and steel mills	Zn, Pb
Copper refinery	Cu, Zn
Waste incineration	Zn, Pb, Cu, Cd, Hg, K
Mineral and material processing	Si, Al, Ca, Mg, K, Sc, Fe, Mn
Seaspray	Na, Cl, S, K
Re-suspended soil	Si, Al, Ca, Mg, Fe, Ti, Sr, Mn, Sc

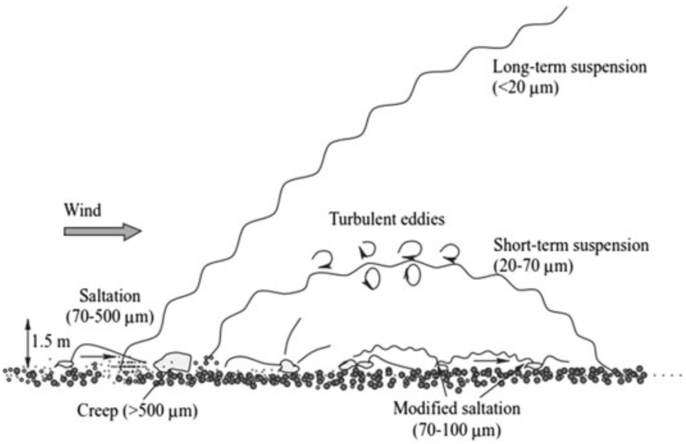

Fig. 4 Illustration of different modes of dust particles motion (Reproduced from [40]) [Permission to reuse granted from Springer Nature]

is extremely favourable. In contrast, dust particles that have diameters smaller than 20 μm are suspended in the atmosphere for several days (i.e., long-term suspension) and can be transported several kilometres from the original location [40–43].

4.3 Factors Governing Dust Particles Deposition on PV Module Surfaces

Dust deposition refers to the settling of particles on the surface during a specific time. It differs from dust accumulation for the reason that the latter indicates the number of dust particles that remains on the surface at the end of a time interval [38]. Dust accumulation on the surfaces of the PV modules is influenced by various factors such as dust properties (size, shape and chemical properties), environmental conditions (wind speed, location and distance of the dust source, dust concentration and weather condition) and PV module characteristics (tilt angle, orientation and properties of surface material) [34, 44]. These factors are discussed in detail in Sects. 4.3.1, 4.3.2, 4.3.3, 4.3.4 and 4.3.5.

4.3.1 Dust Particle Size

The size of the dust is an important parameter for the accumulation of dust particles on the surface of the PV module. This is due to the fact that the adhesion force which is responsible for holding the particles together is inversely proportional to particle diameter [45].

This means that fine dust particles accumulate on the surface of the PV modules more than coarse particles since the former has a strong adhesion force [45–49]. Due to adhesion force, rain has a minimum effect on fine dust particles (2–10 μm) than on large particles (approximately 60 μm) [50]. In a practical situation, this implies that fine dust particles have more effect on the performance of the PV modules than large particles.

4.3.2 Wind Speed, PV Module Tilt Angle and Orientation

The number of dust particles deposited on the PV module depends on the velocity of the wind [51, 52]. Generally, if dust concentration is constant, high wind speeds increase dust deposition on the surface of the PV module [31, 47, 51]. The reason is that high wind speed increases friction velocity which accelerates the transport of more dust particles from their origin sources. However, the rate of dust particles deposition also depends on the PV module tilt angle (β). The amount of dust particles that accumulate on the surface of the PV module is proportional to cos β [53]. This indicates that, for PV modules installed at a fixed angle, dust accumulation decreases

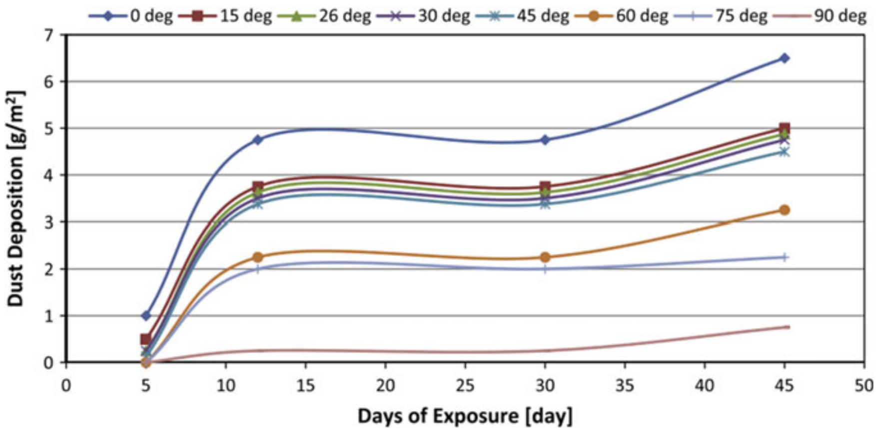

Fig. 5 Effect of PV module tilt angle on dust accumulation (Reproduced from [61]) [Permission to reuse granted from Elsevier]

when PV module tilt angle increases from the horizontal position (i.e., 0º) to the vertical position (i.e., 90º) [7, 34, 47, 54–62]. This is illustrated in Fig. 5. The reason is that dust particles tend to roll down the surface of the PV module due to the gravity effect. In addition, wind direction relative to the surface of the PV module plays an important role in the process of dust accumulation. The surface of the PV module facing the wind direction accumulates more dust than any other orientation [34, 59, 60, 63].

4.3.3 Location and Distance from the Source of the Dust

The number of dust particles that accumulate on the PV modules is influenced by the location and distance from the source of the dust. For example, more dust is accumulated on the PV modules that are installed in locations with high dust concentrations (such as in deserts, mining, along the roads, constructions sites etc.) than those installed in other areas [44, 64–67]. This is due to the fact that even low wind speeds will be able to transport and deposit dust particles on the PV modules. On the other hand, dust concentration is higher for PV modules installed close to the main source of dust than those at a distant [68].

[1] Chemical symbols indicate: BR=Bromine, Pb=Lead, Ba=Barium, Mn=Manganese, Cl=Chlorine, Zn=Zinc, V=Vanadium, Ni=Nickel, Se=Selenium, Sb=Antimony, As=Arsenic, Fe=Iron, Al=Aluminium, ZnO=Zinc oxide, Si=Silicon, K=Potassium, Ca=Calcium, Ti=Titanium, Zn=Zinc, Cr=Chromium, Co=Cobalt, Cu=Copper, S=Sulphur, P=Phosphorus, Ga=Gallium, Cd=Cadmium, Hg=Mercury, Mg=Magnesium, Sc=Scandium, Na=Sodium, Sr=Strontium

4.3.4 Weather Condition

Dust particles from the atmosphere are deposited on the surfaces of the PV modules by both dry and wet deposition mechanisms. Dry deposition refers to dust deposition on the surface of the PV module by one or a combination of the following mechanisms: sedimentation, turbulent diffusion, Brownian diffusion, interception, inertial forces, electrical migration, thermophoresis and diffusiophoresis [45, 69, 70]. Dry deposition involves charging the dust particles during lift-off from the surface which results in either Coulomb force of attraction or repulsion [45, 48]. However, only an attractive force causes dust accumulation on the surface of the PV module. On the contrary, wet dust deposition refers to dust particles deposition on the surface of the PV module through precipitation. In this mechanism, the deposition rate increases significantly as relative humidity increases [71]. Furthermore, high relative humidity promotes the adhesion of dust particles on the surface of the PV module, which becomes very difficult to be blown away [72, 73].

The deposition of dust particles on the surface of the PV module by either dry or wet mechanism is influenced by three main factors, namely season, rainfall and geographical location. For example, dry deposition is dominant in the Mediterranean region and China during summer due to the fact that this is the time with maximum dust concentration and low rainfall [38]. On the other hand, due to high precipitation, wet deposition is dominant in locations such as the North Pacific Ocean, Korea, Taiwan and the eastern sea [74, 75].

4.3.5 Properties of PV Module Surface

For the purpose of protecting the solar cells from physical damage and extreme temperature changes, all PV modules have a front cover which can be glass, epoxy or plastic (Fig. 2). The properties of the front cover material play a critical role in the accumulation of dust on the PV modules. Textured surfaces such as epoxy and plastic tend to trap more dust particles than smooth surfaces such as glass [45, 76–78]. This is due to the fact that epoxy and plastic attract and hold together dust particles more than glass because of the electrostatic attraction force. On the other hand, in some applications (such as electricity generation), PV module tempered glasses are also textured to eliminate optical loss which results from solar radiation reflection. Such glass covers also enhance dust particle trapping that cannot be easily dislodged away by rain or wind [45, 79]. Conversely, non-structured glass also retains dust particles (especially fine dust because smooth surfaces provide extremely large adhesion forces that bind the dust particles to the surface of the PV module) [63, 80]. The adhesion force is so strong that dust particles adhered to the surface of the PV module cannot be easily removed even by wind moving with high speed (e.g., more than 100 km/hour) [81]. Furthermore, the coating also influences significantly the dust deposition rate. The coating of PV module surfaces such as anti-reflection and surface passivation causes the surface to become sticky, thus trapping more dust particles than smooth surfaces [34, 50, 60]. The trapped dust particles settle permanently on the surface of the PV module since they cannot be eroded by wind or rain [45].

5 Effects of Dust on the Performance of PV Modules

The amount of electrical power generated by a PV module is directly proportional to solar radiation reaching the solar cells if other factors (such as operating temperature, non-uniform illumination effect, resistance losses, optical losses, etc.) are kept constant [82, 83]. However, as global solar radiation passes through the atmosphere, a considerable percentage is scattered by dust particles, thus decreasing the beam component of solar radiation on the PV module [31, 84]. On the other hand, when dust particles accumulate on the surface of the PV module, a layer of dust is formed. This layer changes the optical properties of the PV module top surface which in turn reduces the amount of useful solar radiation reaching the solar cells [29, 31, 34, 35, 45, 47, 62, 85–90]. For PV modules integrated into concentrating collectors, the reduction in useful solar radiation due to the presence of dust particles is more than in flat PV modules. This is due to the fact that most CPV modules use only the direct beam component of sunlight [90], thus the sunlight scattered by the dust particles is lost because the concentrator cannot focus it onto the solar cells. In addition, the solar radiation that is not within the acceptance angle of the optical system after passing through the dust layer is also lost. This section discusses the effects of dust on the performance of PV modules.

5.1 Effect of Dust on the PV Module Surface Light Transmittance

The transmittance of light through a material (e.g., glass or plastic) is the ratio of the intensity of light that passes through the material to the intensity of light that passes without it [91, 92]. However, when dust particles accumulate on the surface of the PV module, a layer of dust is formed and this layer changes the optical properties of the PV module surface. As a result, the dust layer on the surface of the PV module can scatter, absorb or redirect the incident sunlight, thus decreasing the useful light reaching the solar cells [7, 29, 31, 85, 93]. The reduction in surface transmissivity of the PV module depends on the dust deposition density, uniformity of the dust layer, size of the dust particles, dust particles chemical composition and wavelength of the sunlight [34, 46, 86].

5.1.1 Variation in Light Transmittance with Dust Particles Deposition Density

The number of dust particles deposited on the surface of the PV module plays a key role in diminishing the transmittance of the incident light. The reduction in the transmittance of the PV module top cover increases as the dust deposition density increases but with a progressively decreasing rate until reaching its upper limit when the effect vanishes [47, 59, 63, 86, 94–96]. As an example, Figs. 6 and 7 illustrate the reduction in PV module surface transmittance as a function of dust particles deposition density. The relationship between the transmittance loss ($\Delta\tau$ in %) and the dust particles accumulation density (ω in g/m^2) can be predicted from Eqs. 2 [47], 3 [59] and 4 [95]. The dependent on the dust particles deposition density on the polyethylene plastic (0.2 mm thick) as PV module top cover can be predicted from Eq. 5 [86]. However, Eq. 3 is only applicable to geographical locations where dust deposition density is between $1.5 < \omega < 9$ gm^{-2}, thus excludes the thinner dust deposition layer of <1.5 gm^{-2}. The light transmittance reduction can also be expressed in terms of normalized transmittance (Fig. 8) which is the ratio between the transmittance of the dusty module to the clean PV module [85].

$$\Delta\tau = 34.37\,\mathrm{erf}\left(0.17\,\omega^{0.8473}\right) \quad \text{for } 0 < \omega < 10 \tag{2}$$

$$\Delta\tau = 0.0381\,\omega^4 - 0.8626\,\omega^3 + 6.4143\,\omega^2 - 15.051\,\omega + 16.769 \quad \text{for } 1.5 < \omega < 9 \tag{3}$$

$$\Delta\tau = 23.27\ln\omega - 23.5 \quad \text{for } 5 \le \omega \le 15 \tag{4}$$

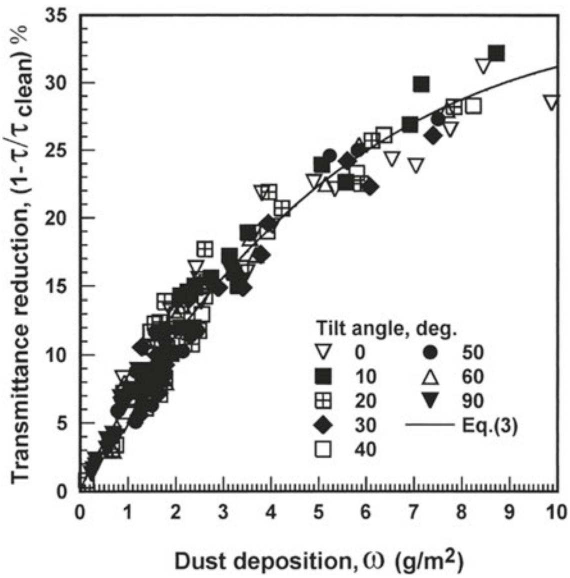

Fig. 6 Reduction in transmittance as a function of dust deposition density; τ is the solar transmittance of the dusty PV module surface and τ_{clean} is the solar transmittance of the clean PV module surface (Reproduced from [47]) [Permission to reuse granted from Elsevier]

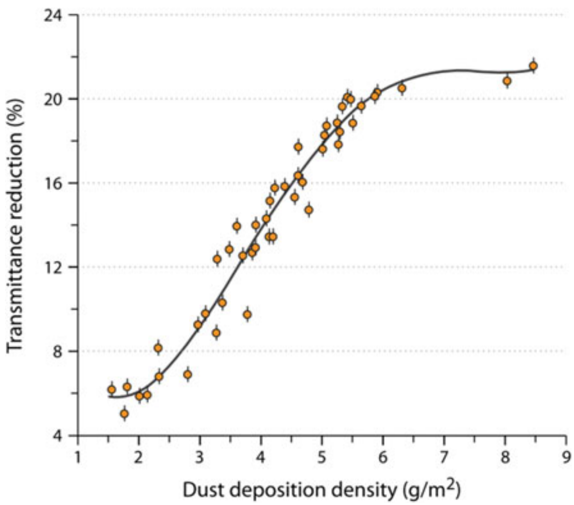

Fig. 7 Reduction in PV module surface transmittance as a function of dust deposition density (Reproduced from [59]) [Permission to reuse granted from Elsevier]

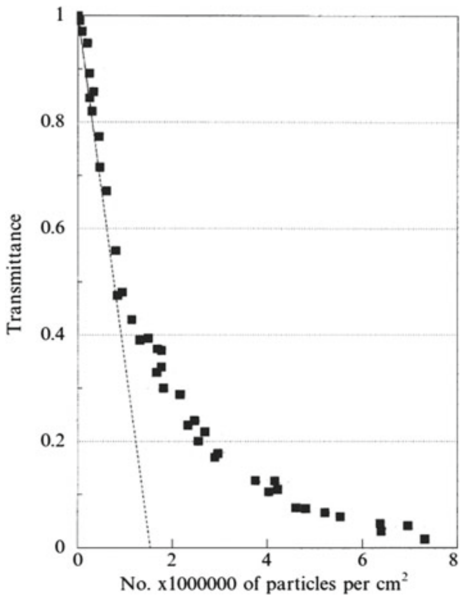

Fig. 8 Light transmittance reduction (at normal incidence angle) as the function of dust particles (6.44 μm) deposition density (Reproduced from [85]) [Permission to reuse granted from Elsevier]

$$\Delta\tau = -0.001335\omega^6 + 0.04398\omega^5 - 0.5427\omega^4 + 3.05\omega^3 - 7.703\omega^2 + 11.19\omega - 2.25$$
$$for\ 0.2 < \omega < 10 \quad (5)$$

On the other hand, the light transmittance loss in PV module surface (glass) increases linearly with an increase in dust particles deposition density when glass plate reflectance and absorption effects are taken into consideration [97]. This is

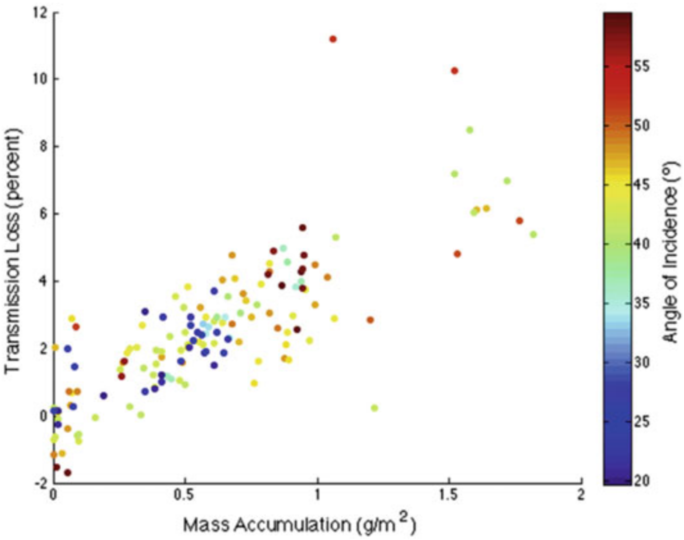

Fig. 9 Transmission loss corrected for angle of incidence compared with the mass of dust deposited on a glass surface (Reproduced from [97]) [Permission to reuse granted from Elsevier]

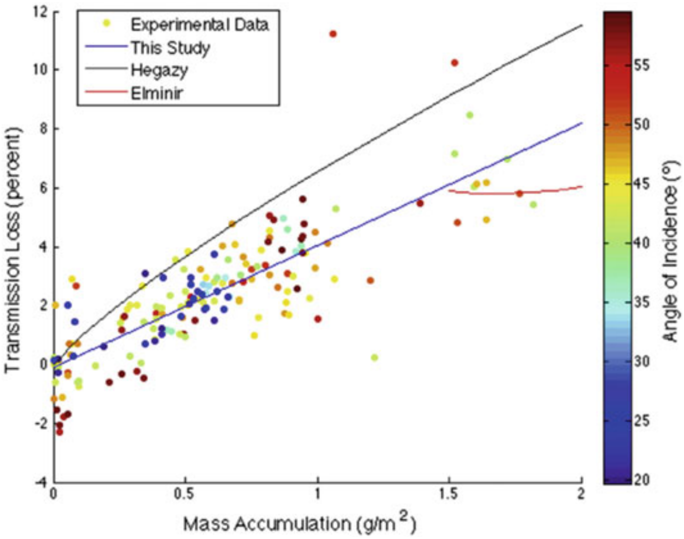

Fig. 10 Comparison of experimental data with different equations: blue line represents Eq. 6, black line represents Eq. 2 and red line represents Eq. 3 (Reproduced from [97]) [Permission to reuse granted from Elsevier]

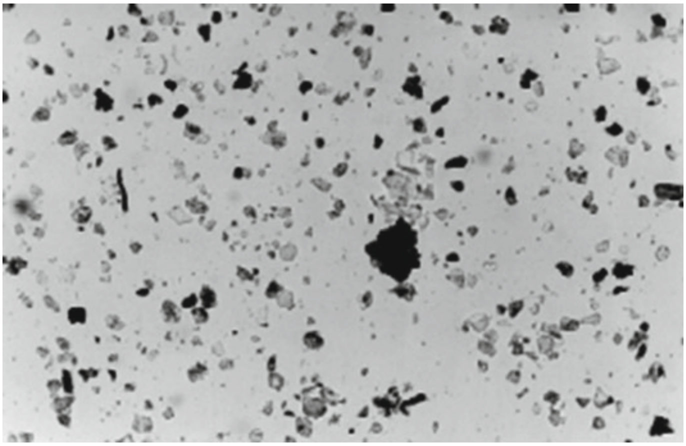

Fig. 11 Non-uniform distribution of dust particles (of different size and type) over the surface of the PV module (particles magnified 20×) (Reproduced from [76]) [Permission to reuse granted from AIP Publishing]

illustrated in Fig. 9 (blue dots) and can be predicted by Eq. 6 [97]. It appears from Fig. 9 that Eq. 6 is only applicable to dust deposition density between $0 < \omega \leq 1.5$ gm^{-2}, but Eq. 6 fits well with Eq. 2 as illustrated in Fig. 10. Therefore, Eq. 6 is also valid to dust deposition density between $0 < \omega < 10$ gm^{-2}.

$$\Delta\tau = 4.1\,\omega \quad \text{for } 0 < \omega < 1.6 \tag{6}$$

5.1.2 Effect of Non-uniformity in Dust Deposition Density on the Transmitted Light

Due to various factors such as dust particles originality, wind speed, the size of the PV module surface and tilt angle, dust particles that accumulate on PV modules may not be uniform over the whole surface of the PV module (Fig. 11). This leads to non-uniform sunlight transmission through the PV module surface since light passing through one area is different from the other areas. The existence of non-uniform illumination on the solar cells reduces substantially the power output and conversion efficiency of the PV module [98].

5.1.3 Variation in Radiation Intensity with Dust Particle Size

The size of the dust particles also influences the amount of light that is transmitted through the top cover of the PV module. Finer dust particles settle on the surface in a more distributed manner than coarser particles, thus minimizing inter-particle gaps

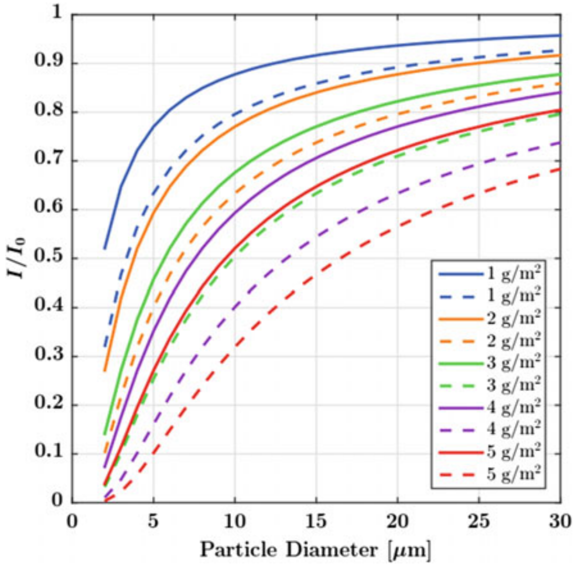

Fig. 12 Variation in solar radiation intensity loss as a function of particle size for different dust concentration densities; the solid and dashed lines denote the transmission loss and reflection loss with $Q_{ext} = 2$ and $Q_{ext} = 3.5$, respectively (Reproduced from [99]) [Permission to reuse granted from the author]

for the light to pass through [59]. This implies that for a particular dust concentration density, as the size of the deposited particles increases, the loss in the incident light decreases [99–101]. Theoretically, this relationship can be determined by using Eq. 1.7a and illustrated in Fig. 12 [99]. This equation uses the concept of particle extinction efficiency (Q_{ext}) which is the sum of the scattering efficiency (Q_{s}) and absorption efficiency (Q_{a}).

$$\frac{I_d}{I_0} = e^{-N\,A_P\,Q_{\text{ext}}} \qquad \text{[monolayer dust particles of diameter } d\text{]} \tag{7a}$$

where I_d is the light intensity after passing through the dust layer and PV module top cover, I_0 is the initial light intensity received by the clean PV module, N is the number of deposited dust particles per unit area, A_P is the projected surface area of the dust particle (in spherical form) which is defined by Eq. 1.7b. For dust particles in the range of 0–2 μm in diameter, Q_{ext} is determined from Mie scattering theory [102].

$$A_p = \pi\left(\frac{d}{2}\right)^2 \tag{7b}$$

5.1.4 Effect of Wavelength on Spectral Selective of Light

The scattering of sunlight by dust particles is governed by the size parameter (α) which is defined by Eq. 8 as the ratio of the dust particle size to the wavelength of the incident radiation (λ) [85]. The scattering of incident light decreases with the increase in wavelength or with the decrease of dust particle size. Due to Mie scattering, the most region of the solar spectrum which is affected by dust is between 350 and 570 nm [7]. In contrast, the transmittance is less spectrally selective at higher wavelengths (>600 nm) [94, 103]. In a practical situation, this implies that wide bandgap materials such as amorphous silicon and cadmium telluride are affected more than the single-crystalline silicon and copper indium gallium selenide modules when they are covered with the same dust layer [103]. The reason is that the spectral response of a-Si and CdTe ranges between 300 and 800 nm.

$$\alpha = \frac{\pi D}{\lambda} \tag{8}$$

where D is the diameter of the dust particle.

5.1.5 Effect of Dust Particles Chemical Composition on Transmittance of Sunlight

The amount of useful light transmitted through the surface of the PV module with a dust layer depends on the nature of the dust particles (i.e., chemical composition and colour). This arises from the fact that different chemical composition has different rates of reflection, transmission and absorption. Red natural soils have the highest reduction in light transmittance than common urban dust particles such as limestone (which consists mostly of calcium carbonate) and carbon-based ash (emitted from thermal power stations or vehicular exhausts) [104]. On the other hand, carbon has higher light transmission reduction than both limestone and cement [100]. This is due to the fact that carbon absorbs solar radiation more effectively than limestone, cement or other similar dust particles.

The reduction in transmittance of the PV module surface has also been correlated with the number of days the PV module has been exposed to the dusty environment [47, 50, 54–57, 60, 86, 105–108], PV module tilt angle [47, 54–57, 59, 60, 109] and orientations [59]. In addition, the mathematical equations that use PV module expose time have been developed to predict the transmittance of light through the PV module surface with dust particles [47, 86, 110]. However, in practical situations, the transmittance of sunlight in the glass cannot be correlated to the exposure time, tilt angle or orientation since these parameters do not influence the transmittance [111]. The exposure time does not provide useful information regarding the amount of sunlight that has been reduced due to the presence of dust particles on the surface of the PV module. Instead, the reduction in solar radiation intensity must be correlated only with the surface mass density of the dust particles on the PV module.

5.2 *Effect of Dust on PV Module Surface Temperature*

The accumulation of dust particles on the surface of the PV module may be uniform or non-uniform. Uniform dust deposition on the surface of the PV module leads to a decrease in the incident radiation causing reduction in surface cell temperature. Therefore, the temperature of a clean PV module is always higher than a similar uniformly dusty covered module [96, 111, 112]. However, non-uniform dust particles deposition on the module gives rise to uneven solar radiation distribution on the solar cells. Under non-uniform illumination, the solar cells in the PV module that are obscured by dust particles produce less current than the fully illuminated solar cells. Yet, the least illuminated solar cells are also forced to carry the same high current as of the other fully illuminated cells. As a result, low-current producing cells tend to operate under reverse bias, dissipating power in the form of heat (hotspot) [113]. The solar cells in the hotspot conditions transfer temperature to the dust particles which overheat the PV module according to their thermal conductivity. Conversely, the hot-spotted cells transfer heat to other solar cells within the PV module by convection (Fig. 13) [94]. Thus, the thermal profile of the PV module with non-uniform dust accumulation is not uniform. For this reason, PV modules with non-uniform dust accumulation have higher surface temperature than clean PV modules (Fig. 14) [45, 89, 94, 114–117]. However, the rate of increase in surface temperature of the PV module varies significantly with the level of non-uniformity (i.e., dust deposition

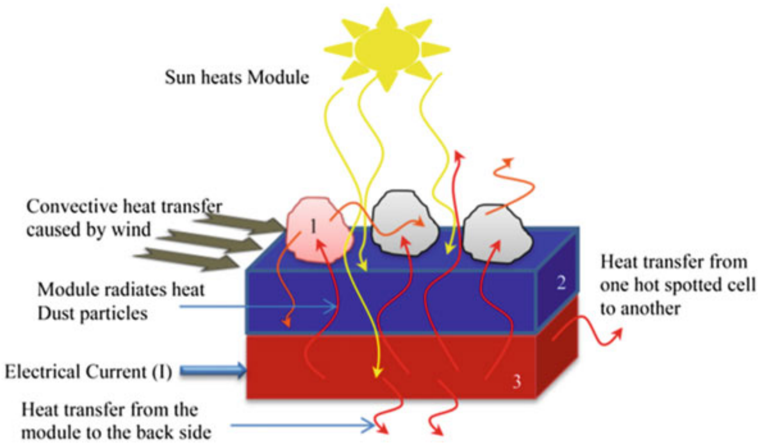

Fig. 13 Cross-section view of the PV module with non-uniform dust accumulation illustrating the mode of heat transfer (numbers indicate: 1—dust particle, 2—PV module glass cover and 3—hot-spotted solar cell) (Reproduced from [94]) [Permission to reuse granted from Elsevier]