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The environmental factors affecting solar photovoltaic output

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ABSTRACT

The global expansion of solar photovoltaics (PV) is central to the global energy transition. As governments aim to triple renewable energy capacity by 2030, solar PV is poised for rapid growth, particularly outside mid-latitude regions (China, Europe, US) where uptake has been highest. These new growth areas have diverse environmental conditions, where factors like higher temperatures and aerosol concentrations strongly impact solar power production. A comprehensive review of these effects therefore aids PV performance and siting optimization. This review examines six key influences: solar irradiance, ambient temperature, atmospheric conditions, terrain effects, extreme weather events, and long-term irradiance changes. First, solar irradiance has strong geographic and temporal variability, making it the most significant factor. Second, raising module temperature reduces efficiency by 0.4–0.5 % per degree Celsius, limiting productivity in hotter climates. Third, atmospheric conditions (clouds, aerosols, pollutants, and dust) can reduce electricity output by up to 60 %, especially in desert regions. Fourth, terrain factors like albedo and snow present mixed effects, with increased reflection boosting output but snow obstructing panels. Fifth, extreme weather like wildfires and hailstorms cause substantial damage, while solar eclipses lead to large but short-lived output losses. Finally, long-term changes in solar irradiance, driven by climate change and air pollutants, present future challenges for maintaining PV efficiency. Optimizing PV systems for diverse climates and mitigating environmental impacts on productivity is important to the continued success of solar photovoltaics. This review highlights the need for tailored strategies to maintain performance in varied and evolving environmental contexts.

Abbreviations and Nomenclature

a-Si	Amorphous Silicon
AM	Air Mass
APE	Average Photon Energy
c-Si	Crystalline Silicon
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
DNI	Direct Normal Irradiance
E	Solar Irradiance
GaAs	Gallium Arsenide
GHI	Global Horizontal Irradiance
Gt	Gigatonnes
GW	Gigawatt
I-V	Current-Voltage
MPP	Maximum Power Point
NOCT	Nominal Operating Cell Temperature
PCM	Phase Change Materials
PR	Performance Ratio
PTC	Photovoltaic USA Test Condition
P-V	Power-Voltage
PV	Photovoltaic
PV/T	Hybrid Photovoltaic/Thermal
STC	Standard Test Conditions

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1. Introduction

At COP28, nations pledged to triple global renewable energy capacity by 2030 [1]. This commitment targets 7500 GW of renewable capacity installed by the end of this decade, the majority of which will be

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solar PV. This transition is urgent, as global CO_2 emissions from energy continued rising in 2022 to a record 36.8 Gt [2]. Solar PV is now central to the global electricity transition due to its rapidly falling costs, scalability, versatility, and sustainability [3,4]. Global installed capacity exceeded 1000 GW in 2023 and is growing by over 20 % annually [5]. Solar PV accounted for approximately 5.5 % of global electricity generation in 2023, increasing from 4.6 % in the previous year [6], and this share is expected to grow faster than any other technology [7].

While supportive renewable energy policies and technological advancements have increased the appeal of solar PV [3], its deployment has been highly concentrated in a relatively narrow range of countries, mainly in mid-to high-latitude countries of Europe, the US, and China as shown in Fig. 1 [5]. Expansion across all world regions – including the diverse climates of deserts, plateaus, tropical and coastal areas – is complicated by the many environmental factors which influence solar PV performance. These factors substantially impact power production, making a comprehensive understanding of their effects necessary for [8,9]:

1. Optimizing performance and maximizing energy yield.
2. Accurately predicting performance for energy planning and setting realistic investor expectations.
3. Managing the variability/intermittency of output for effective grid integration.
4. Evaluating environmental impacts through life cycle assessments, guiding sustainable practices, and reducing carbon footprint.

Since solar PV is central to the global energy transition, this review identifies and quantifies the key environmental factors influencing PV performance and synthesizes current knowledge on these factors. It explores technologies and strategies to mitigate the effects of adverse conditions and examines global-scale long-term changes in solar irradiance and their implications for future solar PV output. Technical factors like cell efficiency, orientation, tracking systems, shading, and durability also affect system performance, and are the subject of other reviews [11–13].

The paper is structured to review six key environmental factors affecting solar PV performance in turn. Section 2 to 7 cover the following topics: solar irradiance, ambient air temperature, atmospheric conditions, terrain effects, extreme events, and long-term changes. Section 8 summarizes the key findings and their implications for the future of solar PV technology.

2. Solar irradiance

The rated performance of solar PV modules (often referred to as solar panels) is defined using Standard Test Conditions (STC), which allow manufacturers to evaluate performance under simulated, reproducible conditions. However, STCs do not broadly represent real-world conditions and can overstate expected output [14], assuming ideal parameters like the irradiance of a clear sunny day, the module temperature of a clear winter day, and the solar spectrum of a clear spring day [15]. In contrast, the Photovoltaics for Utility Scale Application Test Conditions (PTC), established in 1995 by NREL, aim to replicate more realistic conditions, including higher cell temperatures [16]. Both standards, detailed in Table 1, assume a consistent global climate, ignoring regional variances, meaning that ratings will differ at actual installation sites. PTC provides a more conservative assessment, yielding module power ratings and efficiencies that are around one-tenth lower than STC (89.8 $\pm$ 1.7 %), as shown in Fig. 2.

Over-reliance on STC/PTC assessments can yield inaccurate predictions due to the actual environmental conditions in which modules operate [18,19]. Resolving these requires understanding all environmental factors affecting solar PV output [20]. Current research focuses on maximizing internal solar cell efficiencies over optimizing in

Table 1
Comparison of STC and PTC test conditions for evaluating the performance of solar modules [14,16].

Parameters	STC	PTC
Irradiance	1000 Wm^{-2}	1000 Wm^{-2}
Standard Reference Spectrum	AM 1.5	AM 1.5
Solar Cell Temperature	25 °C	45 °C
Ambient Air Temperature	25 °C	20 °C
Wind speed	None	1 m/s (10m above ground)

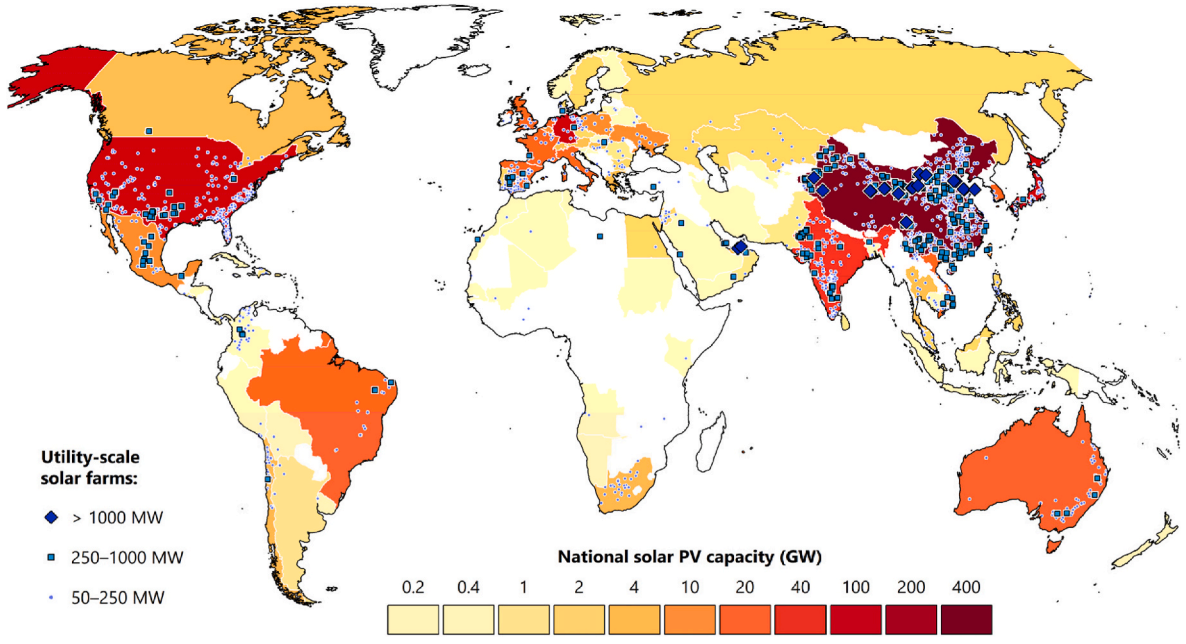


Fig. 1. Global installed solar power capacity, with the locations of the world's largest individual solar farms. Darker colours indicate greater installed capacity and larger farms, countries shown in white have < 0.1 GW installed capacity. National installed capacity data at the end of 2022 from IRENA [5]. Operating solar farms at the end of 2023 from Ref. [10].

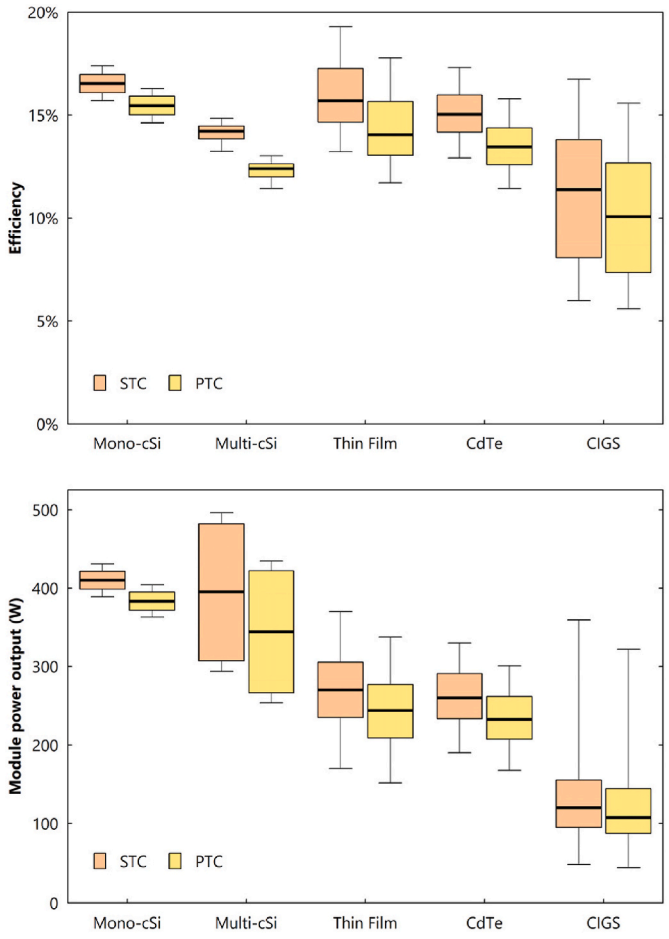


Fig. 2. Summary of the conversion efficiency and power output of 21,000 commercially-available solar PV modules, aggregated by cell technology. Parameters are measured using the STC and PTC standards. Data from the CEC database [17]. The thick line denotes the median coefficient, the shaded area denotes the interquartile range, and whiskers extend to the 5th and 95th percentiles. Mono-cSi: monocrystalline silicon (n = 9614); Multi-cSi: Multicrystalline silicon (n = 11,174); Thin film (n = 561); CdTe: Cadmium Telluride (n = 20); CIGS: Copper Indium Gallium Selenide (n = 8).

real-world conditions [21,22].

2.1. Geographic and temporal variation

Insolation measures the cumulative solar energy an received per unit area over a specified time period, commonly represented using two metrics: Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI). GHI represents the total irradiance received per unit area on a horizontal surface including both direct and diffuse (i.e. scattered) radiation, while DNI represents the direct solar irradiance on a surface perpendicular to the sun, excluding the diffuse component [23]. Both measures are important to PV system performance, as fixed-tilt systems mainly depend on GHI [24], whereas tracking systems benefit more from DNI [25].

The solar zenith angle (the angle between the sun and the vertical) has the strongest influence irradiance levels [26]. A larger zenith angle, indicating the sun is closer to the horizon, results in reduced irradiance because sunlight must travel through a greater thickness of the Earth's atmosphere and thus more of it is scattered. The earth's rotation and seasons determine irradiance intensity and solar zenith angle [27], as illustrated in Fig. 3. Solar cells absorb most energy when sunlight is perpendicular to them as they offer the greatest surface area, and any deviation from this angle reduces electricity output [28]. In summer,

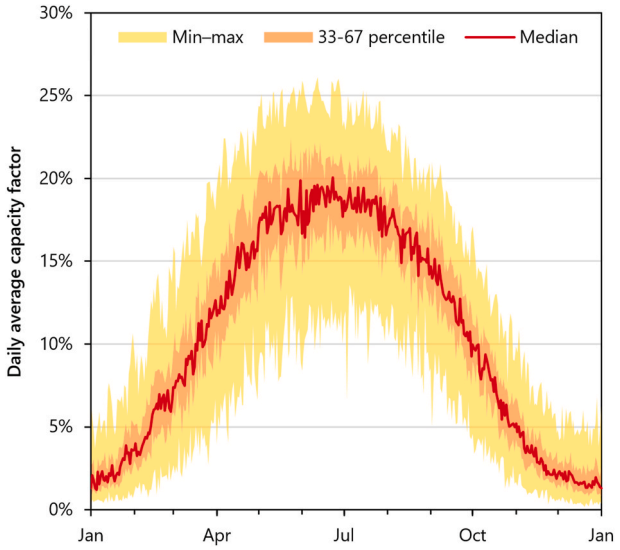


Fig. 3. The temporal variability in solar PV capacity factors in the UK. Daily average capacity factor is summarized over 30 years, highlighting the range over the seasons and variability between years. Capacity factors modelled using the Renewables.ninja software [29]. Reproduced from Ref. [30].

higher sun positions and longer daylight hours yield greater irradiance, with the effect more pronounced when moving to higher latitudes.

Fig. 4 shows the global map of incident solar irradiance. Irradiance is strongest at low latitudes (−30° to +30°) and decreases when moving towards the polar regions due to the increasing zenith angle [31]. Fig. 4 shows that these effects are not uniform, and irradiance received at the surface varies strongly based on geography, cloud cover, and other factors discussed in the later sections. The Earth's elliptical orbit around the sun also causes minor annual fluctuations in solar insolation [32]. Solar irradiance is slightly higher when the Earth is closest to the sun (perihelion) than when it is farther away (aphelion) [33].

2.2. Influence on module performance

Solar irradiance [34] directly impacts electricity output from PV modules, varying with time, location, climate, season, and topography [35]. It affects PV cell performance characteristics, including open-circuit voltage, short-circuit current, cell temperature, and efficiency [28], as well as underlying factors like series resistance, shunt resistance, diode ideality factor, and reverse saturation current [36]. Higher irradiance can impair performance, especially in hotter climates (see Section 3) [37]. A precise understanding of irradiation's impact is essential for optimal solar module installation [38].

Several works have studied the effects of solar irradiance intensity on PV module performance [39,40]. Fig. 5 shows the solar module's current-voltage (I-V) and power-voltage (P-V) curves as a function of irradiance. Current remains constant at the short-circuit current as the voltage increases until it approaches the maximum power point (here, around 37 V), after which it declines rapidly until the open-circuit voltage is reached.

Fig. 6 illustrates the relationships between various performance factors and solar irradiance intensity. Increased solar irradiance reduces parasitic resistance losses [41]. Irradiance has a linear effect on current and log-linear effect on voltage. Solar cell efficiency initially rises, plateauing around 600 W/m^2 before declining slightly up to 1000 W/m^2. The performance ratio (normalised efficiency) is relatively constant across all types of solar cell above 400 W/m^2 but falls by 7–9% at 150 W/m^2 [40]. Series resistance increases with falling irradiance, but the absolute power loss from this is lessened by the current also being lower. Similarly, at lower irradiance the impact of shunt resistance becomes

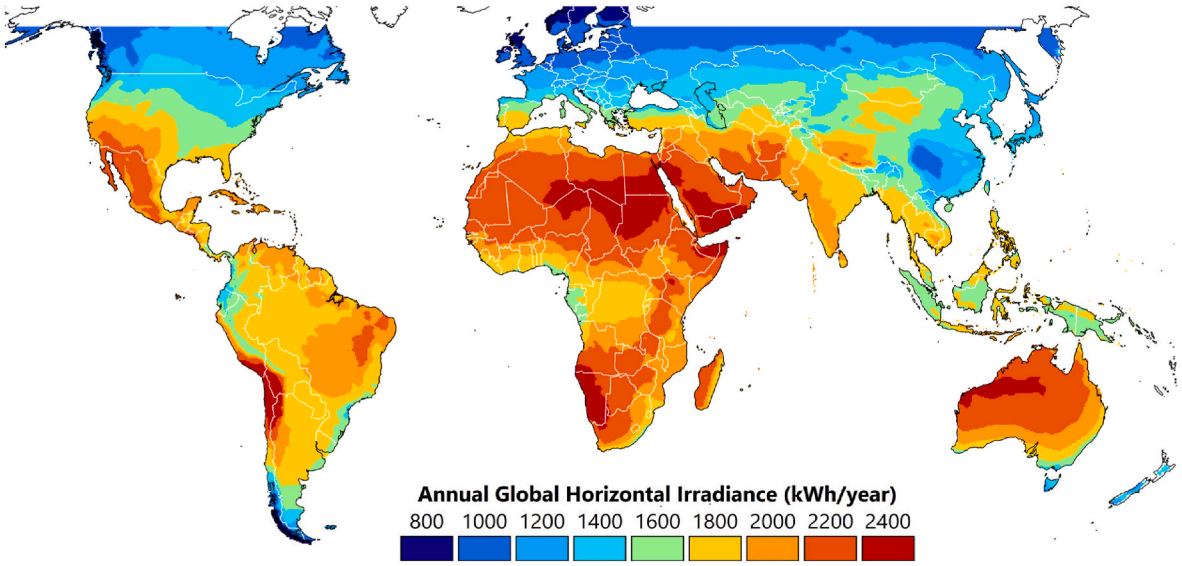


Fig. 4. The geographical variation in global horizontal irradiance (GHI) from 1994/1999/2007 (depending on the location) to 2018 [31].

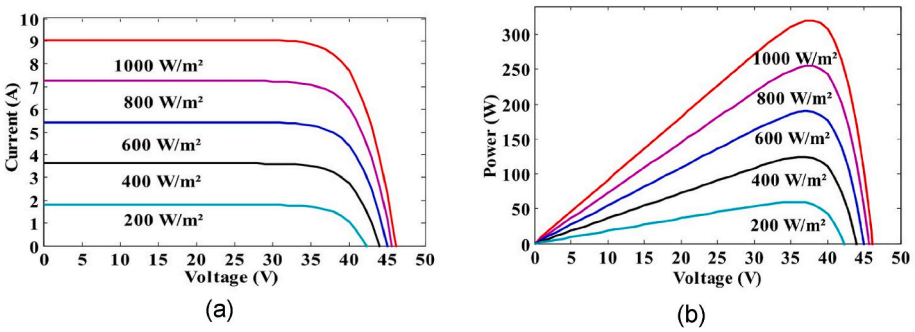


Fig. 5. Solar cell I-V and P-V curves at different irradiance intensities at a constant temperature of 25°C [39]. (a) shows that irradiance has a stronger effect on short-circuit current than on open-circuit voltage. (b) shows that power output increases near-linearly with irradiance.

more noticeable, as shunt pathways tend to carry a fixed amount of leakage current, which becomes more significant when the photo-generated current is lower [40].

2.3. Spectral distribution

PV modules are sensitive to the spectral distribution of solar irradiance [42]. The Average Photon Energy (APE) metric assesses the effect of solar spectrum distribution on outdoor PV module performance [42]. It represents the average energy of photons in the spectrum and is the ratio of integrated irradiance to photon flux density [43]. APE incorporates environmental factors like air mass, cloud cover, and water content [44]. APE values vary with location and season and indicate the spectral shift: higher values suggest a blue-shift, while lower values indicate a red-shift [45,46]. APE influences the open-circuit current even under constant solar irradiance [43]. Fig. 7 shows spectral irradiances with different APE values in three wavelength ranges [47].

Fig. 8 illustrates the diverse sensitivity of solar technologies [48]. Blue-rich spectra improve the performance of hydrogenated amorphous silicon (a-Si:H) and hydrogenated amorphous silicon/hydrogenated microcrystalline silicon hetero-junction (a-Si:H/μc-Si:H) modules as APE increases, but negatively affect copper indium gallium selenide sulphide (CIGS) modules [49]. CIGS modules with a larger bandgap convert blue light efficiently, particularly in summer conditions, showing the importance of spectral distribution on cells with wider bandgaps or multi-junction devices [50].

Thin-film PV systems are particularly sensitive to daily and seasonal changes in spectral distribution [49,51]. Amorphous silicon (a-Si) cells, with narrow blue-rich absorption bands, are particularly affected [52,53]. Seasonal variations have a large impact on a-Si cells [54], and crystalline silicon (c-Si), copper indium diselenide, gallium arsenide (GaAs), and cadmium telluride (CdTe) devices also show distinct spectral responses, making them more sensitive to fluctuations [55–58]. This sensitivity is more pronounced for a-Si and GaAs devices outside mid-latitudes [56]. Despite its importance, spectral distribution, as reflected in APE, is often overlooked in PV modules' performance assessment [59,60]. Bliss [61], and Nagae [62], have therefore developed models to isolate spectral distribution effects from other variables influencing solar module performance.

3. Ambient air temperature

A typical PV module converts 6–20 % of incident sunlight into electricity [63], and incoming solar irradiance that is not converted or reflected generates heat, increasing the PV module's temperature [64]. This heating effect means cell temperatures correlate more strongly with irradiation than ambient air temperature [65,66], although higher ambient temperatures hinder cooling and thus increase cell temperatures. Module operating temperature is determined by the balance of heat generation and heat loss to the environment. Heat production by solar PV farms can raise the surrounding temperature [67], impacting heat dissipation from cells. There is an inverse relationship between PV

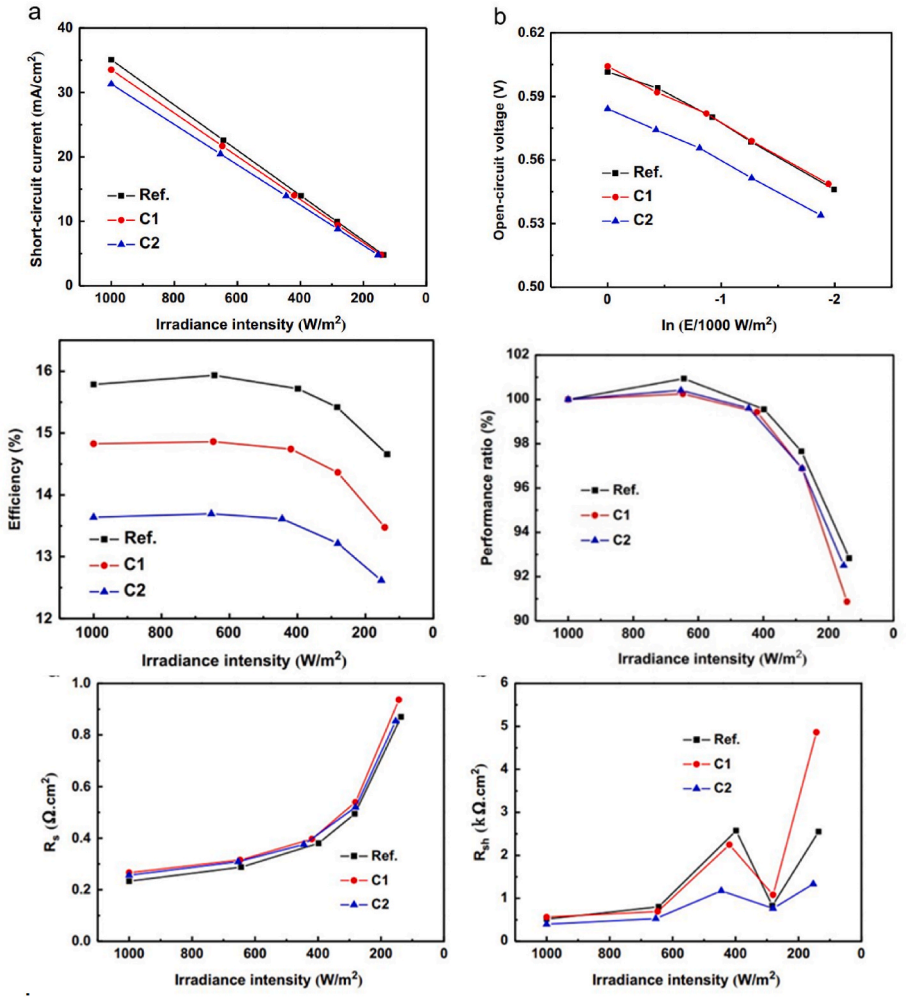


Fig. 6. Relationships between irradiance and various operating parameters of solar cells [40]. (a) shows the linear relationship for short-circuit current density, (b) shows the logarithmic relationship for open-circuit voltage, (c) and (d) show the relationship with efficiency and performance ratio. (e) shows series resistance (R_s) and (f) shows shunt resistance (R_{sh}), which decrease with irradiance [40]. Lines refer to a standard reference B-doped silicon crystal (Ref.), and compensated silicon crystals created with electronic grade silicon doped with boron (C1) and phosphorus (C2).

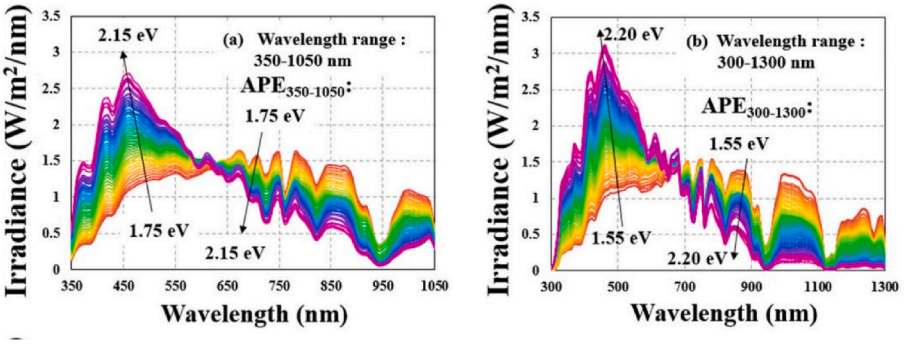


Fig. 7. Spectral irradiance with different APE values. Spectral irradiances in two wavelength bands with varying APE values: 350–1050 nm and 300–1300 nm. Total irradiances in these wavelength ranges were 792 and 923 W/m^2. APE: Average Photon Energy [47].

cell temperature and its efficiency and output [64,65,68]. The temperature coefficient of power quantifies efficiency loss due to temperature. Furthermore, solar modules at high temperature experience more rapid degradation and lower lifetimes [69,70].

3.1. Heating

Solar insolation and ambient air temperature are the two main environmental factors affecting solar PV output [71]. Whereas irradiance has a stronger effect on current, temperature predominantly affects voltage. Fig. 9 illustrates the impact of temperature on solar module power output. Real-world power delivery can deviate by up to 10 %

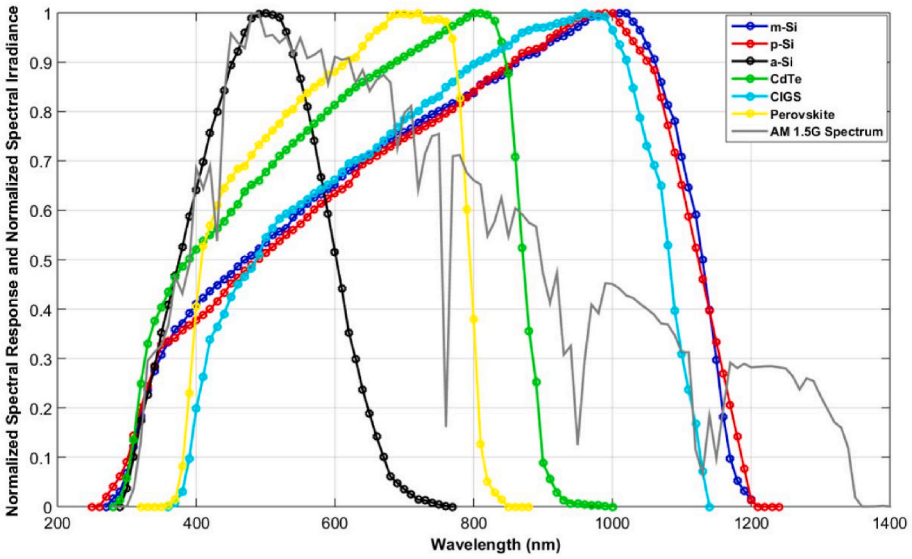


Fig. 8. The different spectral response characteristics of various solar module technologies. m-Si: monocrystalline silicon; p-Si: polycrystalline silicon; a-Si: amorphous silicon; CdTe: cadmium-telluride; CIGS: copper indium gallium selenide sulphide; AM 1.5G: Air Mass 1.5 global spectrum [48].

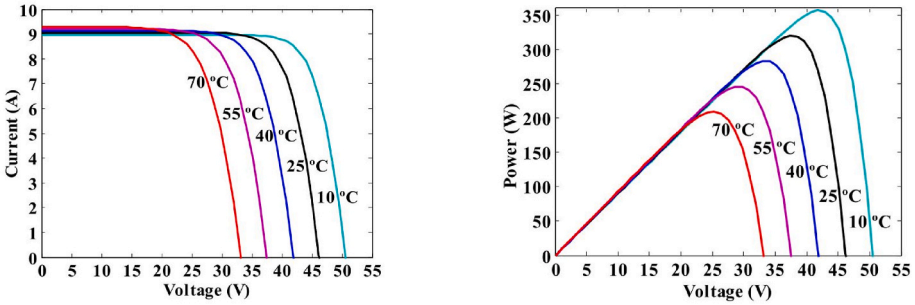


Fig. 9. Solar cell I-V and P-V curves at different temperatures at a constant irradiance intensity of 1000 W/m^2 [39]. (left) shows that temperature has a stronger effect on open-circuit voltage than the increase in short-circuit current. (right) shows that power output decreases near-linearly with temperature [39].

from rated capacity due to temperature elevation at the module surface, which routinely exceeds standard test conditions (STC).

The I-V and P-V characteristics in Fig. 9 demonstrate a slight increase in short-circuit current and a large decrease in open-circuit voltage as temperature rises, reducing power output and thus efficiency. The minor increase in current results from a narrowed band gap at higher

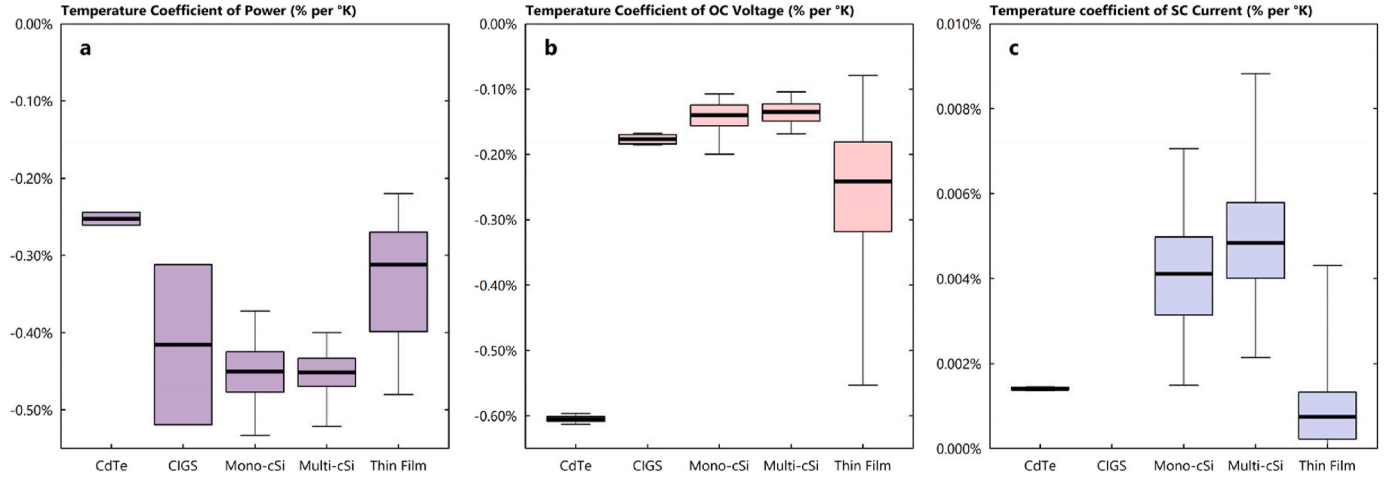


Fig. 10. Summary of the temperature coefficients from 21,000 commercially-available solar PV modules, aggregated by cell technology. Coefficients are given for (a) maximum power production, (b) open-circuit voltage, and (c) short-circuit current. Data from the CEC database [17]. The thick line denotes the median coefficient, the shaded area denotes the interquartile range, and whiskers extend to the 5th and 95th percentiles. CdTe: Cadmium Telluride (n = 20); CIGS: Copper Indium Gallium Selenide (n = 8); Mono-cSi: monocrystalline silicon (n = 9614); Multi-cSi: Multicrystalline silicon (n = 11,174); Thin film (n = 561).

temperature [28], lowering the energy needed for electron-hole pair creation, and increasing phonon density and state density in the conduction and valence bands [72]. The decrease in open-circuit voltage is due to increased leakage current [40]. Additionally, the shrinking band gap increases intrinsic carrier concentration, negatively affecting solar cell performance [73]. Furthermore, module temperature and PV cell material bandgap energy are closely related, with bandgap energy typically decreasing at high operating temperature.

PV modules are characterized temperature coefficients which measure the change in operating performance per degree Kelvin (or Celsius) rise. These coefficients can relate to power, voltage, current or efficiency, and vary with cell technology and design [74]. Manufacturers provide these coefficients from performance assessment under varying temperatures, summarized in Fig. 10. Commercial c-Si cells typically experience 0.45 % drop in efficiency per °C rise in temperature, compared to 0.25 % per °C for a-Si [74,75]. A polycrystalline module operating at 45 °C should therefore produce 9 % less power than its predicted rating via STC. The temperature coefficient for open-circuit voltage ranges from −3 to −5 mV per °C [76]. In c-Si solar cells, open circuit voltage decreases by about 2.3 mV per °C when temperature is beyond 25 °C [77]. Higher voltage cells are therefore less affected by temperature.

Fig. 10 shows that CdTe technology typically has a temperature coefficient in the range of −0.24 % to −0.26 % per °K, meaning efficiency drops less than other technologies at high temperatures, making it suitable in hot climates. CIGS modules have a temperature coefficient in the range of −0.31 % to −0.52 % per °K, albeit from a small sample size as these are not widely available commercially. In contrast, monocrystalline silicon and multi-crystalline silicon modules have moderate and very similar coefficients, −0.425 % to −0.447 %, and −0.434 % to −0.470 % respectively. Thin film technologies vary widely, with temperature coefficients of −0.27 % to −0.40 % per °K, depending on their composition. Those with larger temperature coefficients are less suited to hot climates, but may be more cost-effective in certain scenarios. These coefficients are critical to understanding PV system performance in real-world applications, as operating temperatures vary widely between locations and over time, and temperature coefficients vary between technologies and specific manufacturer designs and products.

All PV systems experience performance degradation over their lifetime which leads to reduced energy output [78–80], in common with other renewable technologies [81]. Elevated temperatures accelerate the degradation of PV cells and other system components, such as through the breakdown of adhesive seals, corrosion, discoloration, bulging, delamination, glass or cell fractures, and interconnection failures [82]. The degradation rate of PV modules approximately doubles for every 10 °C increase in operating temperature [83].

The Nominal Operating Cell Temperature (NOCT) standardized test measures the temperature of cells at open-circuit in a module under specific conditions: ambient temperature of 20 °C, irradiance of 800 W/m^2, 1 m/s wind speed, and an open back side. It provides a more realistic assessment of module operating conditions, but is challenging to measure in real-world systems and manufacturers express doubts over its uncertainty [84]. Equation (1) gives an approximation for calculating cell temperature:

$$T_{cell} = T_{air} + \frac{NOCT - 20}{800} E \tag{1}$$

Where T_{cell} is cell temperature, T_{air} is ambient temperature, $NOCT$ is the module temperature under the standard test conditions, and E is solar irradiance in W/m^2 [85]. The average NOCT for commercial cSi modules is 46.5 °C, with an interquartile range of 45.5–47.5 °C, as shown in Fig. 11.

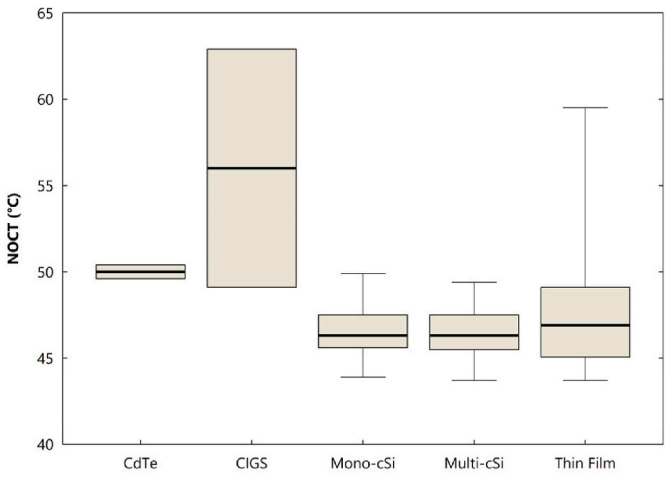


Fig. 11. The Nominal Operating Cell Temperature (NOCT) for 21,000 commercially-available solar PV modules, aggregated by cell technology. Data from the CEC database [17]. Figure design and nomenclature is the same as for Fig. 10.

3.2. Cooling

Cooling solar modules can mitigate the effects of elevated cell temperatures, increasing efficiency and power output, and extending system lifetime. Cooling techniques for PV modules fall into two categories: active and passive [83]. The choice between methods depends on system size and economic viability: single cells typically require only passive cooling, densely packed cells in high solar concentrations require active cooling [86].

Passive cooling without additional electrical power relies on installation strategies that increase heat transfer. Techniques include submerging modules in water, and attaching heat sinks or fins behind the modules to promote natural convection and radiation [83]. Building-mounted PV modules should be mounted clear of the roof, or with ducts under the modules, to allow cooling from air flowing beneath them [63,82]. Phase change materials (PCM) absorb heat from the PV modules, storing it without increasing the module temperature until the PCM reaches its melting point [83,87]. Similarly, evaporative cooling utilizes the latent heat of evaporation. Heat pipes function as compact refrigeration cycles, with separate evaporative and condenser sections for vapor-liquid exchange.

Active cooling methods require external power for pumps and fans [82], so the parasitic load of these systems reduces the net power output from the PV system [88]. Techniques include misting or spraying water onto PV modules, or using DC fans for forced air cooling [82,83]. Water-cooling is generally more effective than air-cooling due to its superior heat transfer properties. Hybrid Photovoltaic/Thermal (PV/T) systems are also widely used, where the water or air that is circulated to cool modules is repurposed for domestic applications like space and water pre-heating [85]. Fig. 12 categorizes various PV cooling methods, and for further reading, Bilen and Erdoğan [89] perform a systematic review of cooling effects on PV and thermal modules.

4. Atmospheric conditions

Several atmospheric conditions can affect the output of solar PV systems. This section considers five factors: clouds, pollutants, humidity, dust, and wind speeds.

4.1. Cloud characteristics

Cloud cover strongly impacts solar PV output, primarily by reducing the Direct Normal Irradiance (DNI) received [90,91]. Cloud cover

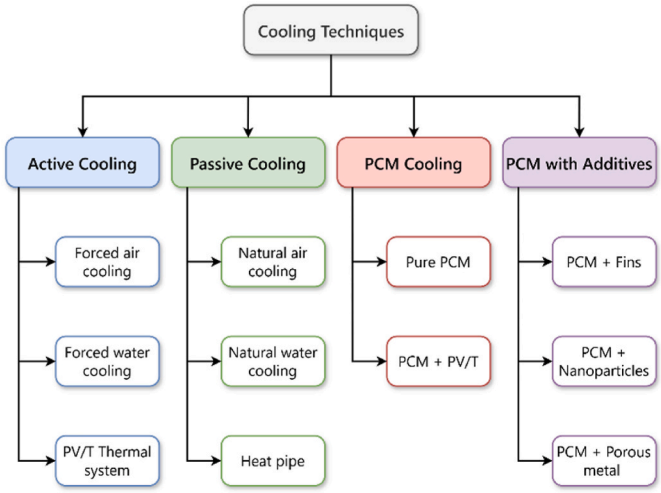


Fig. 12. Classification of different PV module cooling methods, based on [87]. PCM: phase change material; PV/T: photovoltaic/thermal.

reduces PV capacity factors by 50 % in Northern Europe, and by 15–30 % in the US and China [92]. Aside from the extent of cloud cover, impact depends on clouds' physical characteristics such as coverage, shape, optical thickness, liquid water content, and particle size distribution. Thick clouds can block direct sunlight, increasing scattering and diffusion [93], and they can reflect sunlight through cloud albedo effects [60,94].

Puffy, white Cumulus Clouds partially obscure the sun, reducing irradiance, while their movement across the sky creates alternating periods of shade and sunlight, resulting in fluctuating irradiance. Low, uniform Stratus Clouds can create diffuse lighting reducing direct insolation. Conversely, high-altitude Cirrus Clouds may attenuate sunlight but generally allow much to pass through. The denser the cloud cover, the more pronounced the attenuation.

The "edge of cloud" effect (also called "cloud edge glint" or "cloud enhancement") occurs when sunlight is concentrated at cloud edges due to scattering and bending through cloud droplets. This can temporarily increase solar module efficiency when a cloud partially obscures the sun [95], as the cloud edges act as lenses, focusing more sunlight on a specific area. This brief increase in irradiance can be harnessed by solar tracking systems to maximize energy generation during partially cloudy conditions. Cloud cover tends to be short-term [96,97], resulting in irregular, uneven solar irradiance [90,91]. The transparency of clouds determines the extent of light penetration [60]. Forecasting short-term output is more accurate with squall line clouds (0 % light penetration) than with cumulus clouds [98]. Squall lines are predictable and transient, allowing faster resumption of power generation after their passage. In contrast, cumulus clouds are highly variable and can prolong reductions in solar PV output.

4.2. Atmospheric pollutants and particulates

Atmospheric aerosols scatter and absorb sunlight reducing the amount reaching the Earth's surface. Aerosols are a suspension of microscopic solid and liquid particles in the atmosphere, such as dust, haze, fog, volcanic ash, sea salt, wildfire smoke, and pollution from both natural and human activities [99]. Atmospheric aerosols reduce PV capacity factors by up to 20 % dependent on world region [92]. For example, regions of South Korea with poor air quality experience a 15–24 % drop in utility-scale PV generation due to aerosols [100]. Similarly, air pollution in China is estimated to reduce PV CF by 11-15% [101]. Two factors affect direct irradiance: (1) the scattering of light by air molecules, water vapor, clouds, and dust, and (2) the absorption of light by substances like O_3, H_2O, and CO_2 [102].

The dispersion of light (Rayleigh scattering) is stronger at shorter wavelengths (blue light) due to its dependence on the fourth power of wavelength (λ^{-4}). Around 10 % of incoming solar irradiance is scattered on a clear day [103]. The attenuation of solar irradiance by pollutants and particulates is called "solar irradiance reduction" or "solar dimming". This varies by location, weather conditions, and pollutant concentration. Fig. 13 shows the global average aerosol optical depth (AOD), indicating the extent to which irradiance is blocked by scattering and absorption processes [104]. Areas of high AOD include the Sahara Desert and Middle East due to desert dust and dust storms [105]; India, China and Southeast Asia due to pollution from coal-fired power stations, vehicles and industry [106]; Canada, Western US and the Amazon Rainforest due to wildfires [107], and the latter because of deforestation and agricultural burning. Across India and Southeast Asia, agricultural emissions from slash-and-burn farming are also a major contributor [108].

4.3. Dust deposition

Aerosols with particles sizes ranging from 0.1 μm to 1000 μm can accumulate on PV surfaces over time, commonly referred to as soiling. Dust deposition is the third major factor that affects the efficiency of a PV module, after solar irradiance and temperature [110,111], making it important to address for optimal system performance. Dust on the module surfaces reduces incoming irradiance by scattering or absorbing the incident sunlight [77,112].

Fig. 14 depicts the global distribution of dust emissions. The principal dust sources are the world's seven main deserts in North Africa, the Middle East/Central Asia, East Asia, North America, South America, South Africa, and Australia. The North Atlantic has the highest dust deposition, receiving 43 % of the global total, mostly due to Saharan dust. The Indian Ocean is the second-largest location for dust deposition (25 %) from North Africa, Arabia, Central Asia, and Australia [113].

Factors affecting dust deposition include environmental conditions (wind speed, proximity to dust sources, concentration of dust, and weather conditions), dust properties (size, shape, and chemical composition), and PV module characteristics (tilt angle, orientation, and surface material properties) [77]. A dust density of 10–30 g/m^2 is sufficient to reduce panel output by 20 % [111]. Larger particles are more influenced by gravity and inertia, and so settle faster. Smaller particles remain airborne for longer, leading to quicker accumulation of fine dust. Fig. 15 summarizes the different factors affecting dust accumulation on solar PV modules.

Glass surfaces attract less dust than tedlar, epoxy, or plastics [115,116]. Wind speed, direction, and dust properties influence dust accumulation [112,117], with light breezes increasing dust accumulation and strong winds clearing modules of dust [118]. Tilt angle inversely affects dust accumulation [119], with dust accumulation on a module tilted at 30° causing a 1 % decrease in output [120]. Dust on solar modules creates hot spots, reducing current flow and dissipating energy instead of generating it [121]. Dust affects current more than voltage, as short-circuit current gradually decreases with increasing dust deposition density [122,123]. Power output reduction is linked to dust layer thickness rather than exposure duration [124,125]. Dust may also accelerate PV module degradation due to corrosive and acidic particles [118,126]. Overheating can also accelerate cell failure if modules are not regularly cleaned [127].

Dust deposition can reduce power output by up to 60 % in desert regions [128]. Although numerous studies have examined the effects of dust [129,130,131–136], their findings are often site-specific and not applicable more broadly [133,134]. However, Elminir [137], suggest that findings may apply to locations with similar climates and PV module mounting techniques. Kimber [135] and Coello and Boyle [136] provide simple models for quantifying the impact of dust soiling on modules.

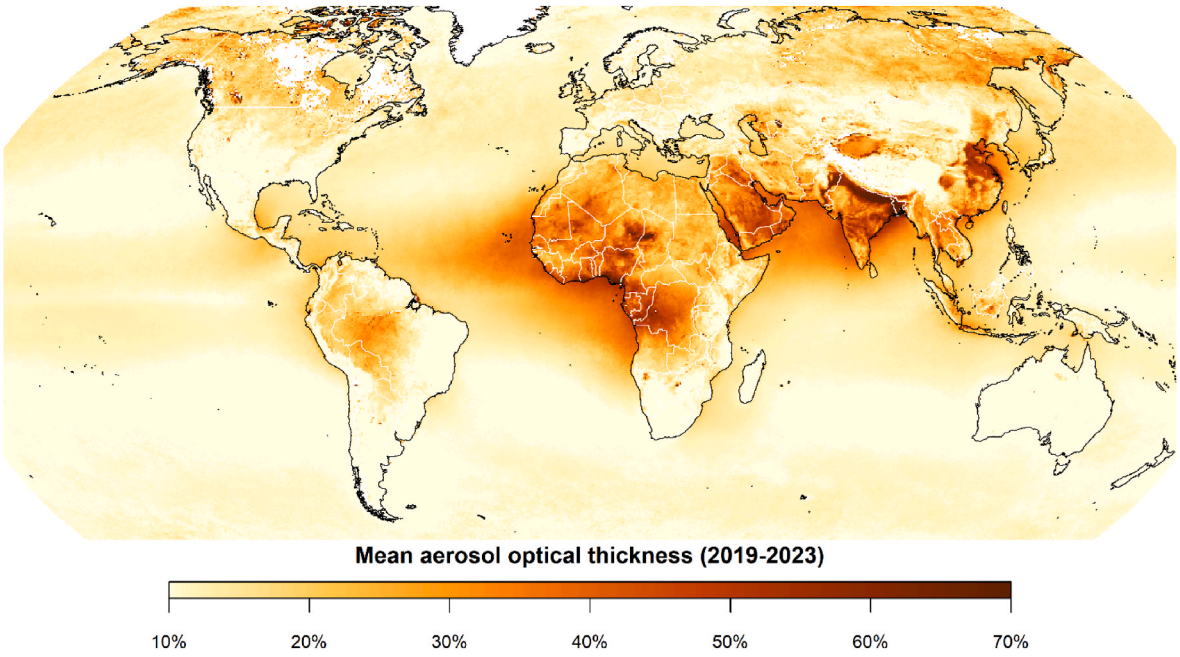


Fig. 13. Global map of aerosol optical thickness averaged over January 2019 to December 2023. Darker areas indicate higher aerosol levels, white patches indicate no data. Data from Ref. [109].

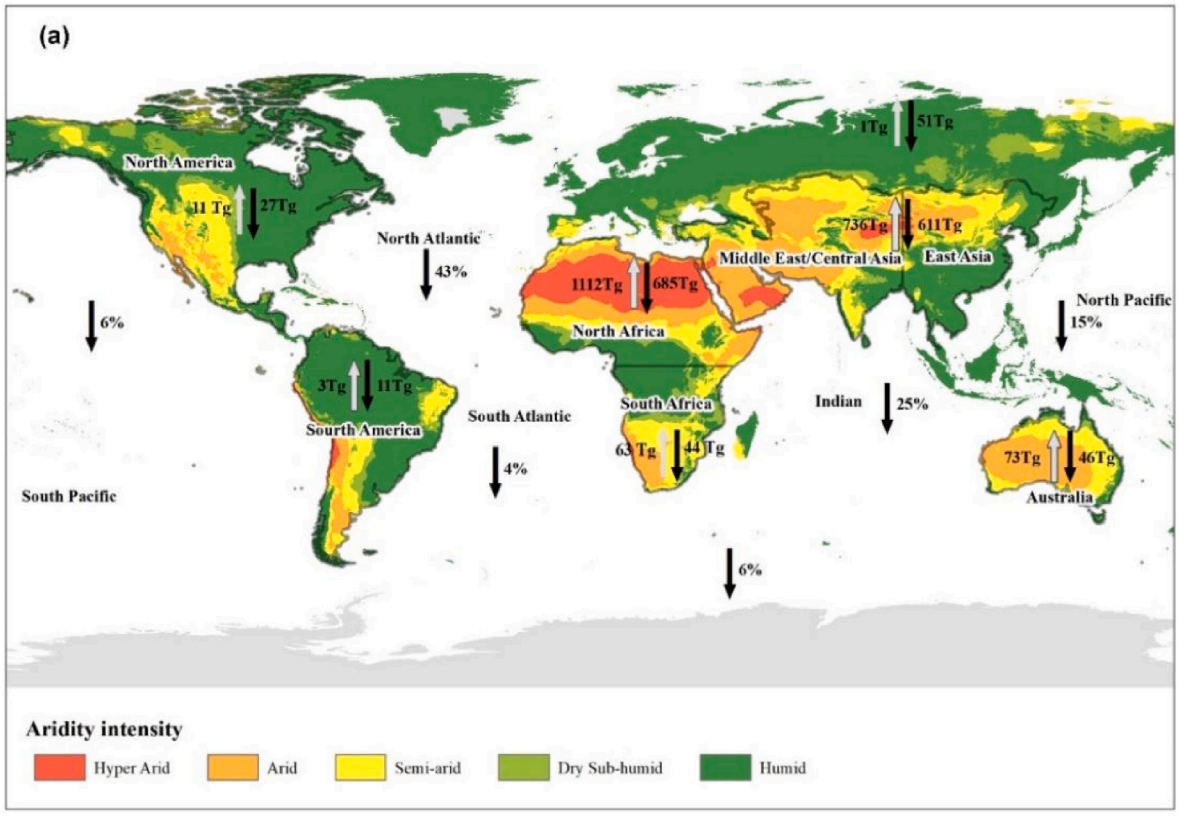


Fig. 14. Global map of dust emissions and deposition. Grey and black arrows indicate dust emission and deposition respectively, as shares of the total global dust cycle [113].

4.4. Dust cleaning

Extensive studies [114,138,139] have explored strategies for dust management and cleaning to mitigate its effects. Cleaning is a major operating expense in desert regions [133], but can increase PV capacity factors by 50–100 % even if only performed quarterly [92]. Cleaning methods can be classified under four broad categories as illustrated in Fig. 16 [114,139,140]: (i) mechanical, (ii) self-cleaning, (iii) electrostatic, and (iv) natural. The choice of cleaning method depends on dust particle size [127].

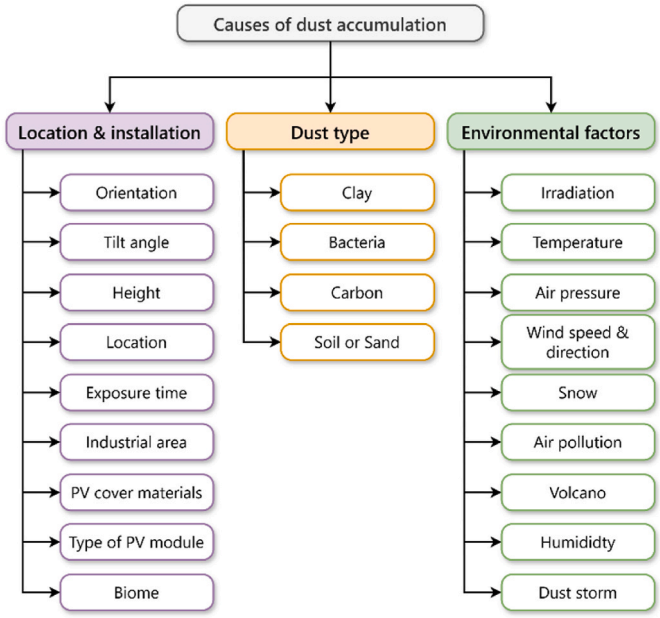


Fig. 15. Classification of the factors affecting dust accumulation on solar PV modules, based on [114].

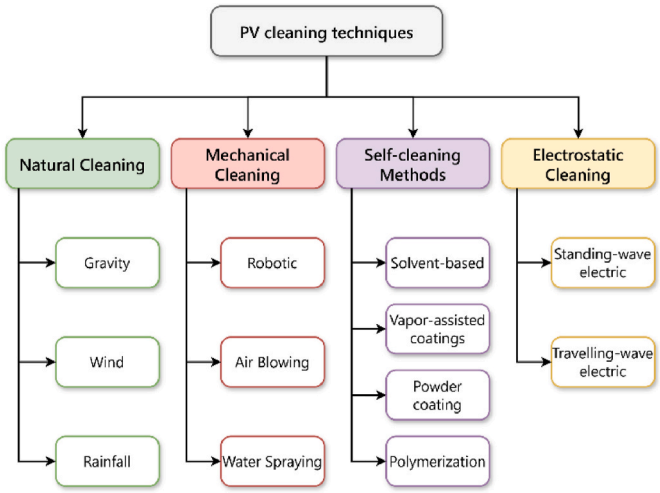


Fig. 16. Classification of PV dust cleaning methods, based on [114].

Wind and rain can naturally clean PV surfaces by blowing or washing dust away. Rain for cleaning is viable only in areas with consistent rainfall [132]. However, in regions with limited rainfall and frequent dust storms, such as North Africa, East Asia, and the Middle East [141], natural cleaning is ineffective [142–144].

Mechanical cleaning uses engines, robots or high-pressure water systems, potentially including water storage tanks [112,140]. These methods require substantial electrical energy and moderate costs from initial investment and maintenance [110]. Water-based cleaning faces additional costs in water-stressed regions, and so water-free cleaning techniques should be used preferentially [92]. Each method provides distinct benefits and drawbacks.

Self-cleaning systems offer an alternative for maintaining PV module performance by removing dust, although they are less effective at removing air pollutants. Self-cleaning coatings include hydrophobic and super-hydrophilic types [145,146]. Hydrophobic coatings repel water and reduce dust adhesion through micro- or nano-scale textures that lower surface energy, inspired by the lotus leaf [147]. This causes water droplets to form spherical shapes with a high contact angle, meaning they bead up and roll off the surface, carrying away dirt particles.

These coatings typically use hydrophobic materials like fluoropolymers or silanes with nanostructured surfaces [148]. Super-hydrophilic coatings undergo photocatalysis when exposed to sunlight, chemically decomposing dirt and impurities. They modify material surfaces to attract and disperse water, creating self-cleaning properties by reducing water contact angles to nearly zero degrees [149]. Common modifications include adding hydroxyl (-OH) groups or applying thin films containing hydrophilic materials like titanium dioxide (TiO_2) or silica (SiO_2). These coating techniques, along with chemical cleaning can achieve a cleaning efficiency of 72 % without extra components or water [150,151]. Technologies that monitor and remove impurities using wave motion can be effective [129] with the potential to eliminate 80 % of dust in 2 min [152].

Corona discharge ionizes the air surrounding the surface, creating charged species that interact with dust particles. Triboelectric charging occurs when two dissimilar materials contact and transfer charge. Induction charging uses a separate charged object: once dust is attracted to the charged surface, it must be detached for effective cleaning, typically through mechanical vibration, air flow, and reverse polarity [153,154].

Electrostatic cleaning is suitable in regions facing water scarcity, offering swift removal of dust with less energy and no need for water and human intervention [154]. In Jordan, electrostatic dust cleaning reduced power loss from 5.9 % in naturally cleaned modules to 4.6 % [155]. Transparent self-cleaning dust shields using electromagnetic fields have also demonstrated high efficiency [156], removing 90 % of dust in under 30 min without the need for water or labor [157]. While most studies focused on the negative impacts of dust, a tenuous positive impact is that dust reduces large-angle reflections from the cover glass, increasing captured radiation [127].

4.5. Humidity

Humidity generally exhibits an inverse relationship with solar PV power output [158,159], and Fig. 17 shows the reduction in performance as humidity rises. Water droplets in the air refract, reflect, and diffract light, reducing the intensity incident on solar cells [160,161]. It also causes fine particles to accumulate on the module surface, impairing light transmission [162]. Humidity also accelerates cell degradation through encapsulant delamination [161,163]. However, one positive feedback is that increased humidity improves a module's efficiency by lowering its temperature, with a 1 % increase in humidity reducing

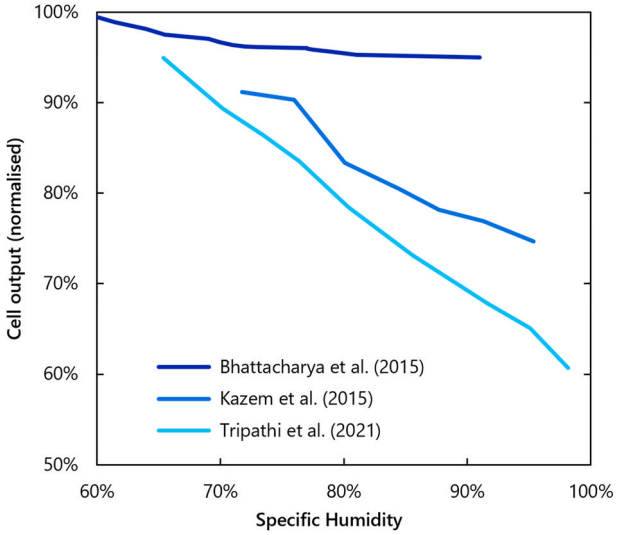


Fig. 17. Variation of PV module efficiency with humidity. Data from Refs. [165–167].

module temperature by 0.94 °C [164].

4.6. Wind

The interaction between wind and PV is complex. Wind increases efficiency by cooling modules, especially during peak sunlight hours [168,169], and reduces soiling by blowing away accumulation of dust and snow [131,170]. However, wind can also deposit dust or snow [118,134], and keeps particles airborne, causing light scattering [170]. Generally, lower wind speeds promote dust and particle deposition, while higher speeds clear modules [118,134]. Extreme winds conditions can compromise structural security [171,172], requiring adequate design margins.

The dynamics of wind flow over module surfaces create lift forces or torque [173], and modules situated closer to the ground experience stronger lift forces [172,174]. Guide plates and end plates are recommended to mitigate wind forces [174,175]. Modules at the edges of a farm shelter those at the interior [175], reducing wind stress [171,176], with the effect dependent on array spacing [173]. Fences can also provide similar sheltering effect [175].

5. Terrain effects

This section explores the impact of terrain characteristics on solar PV

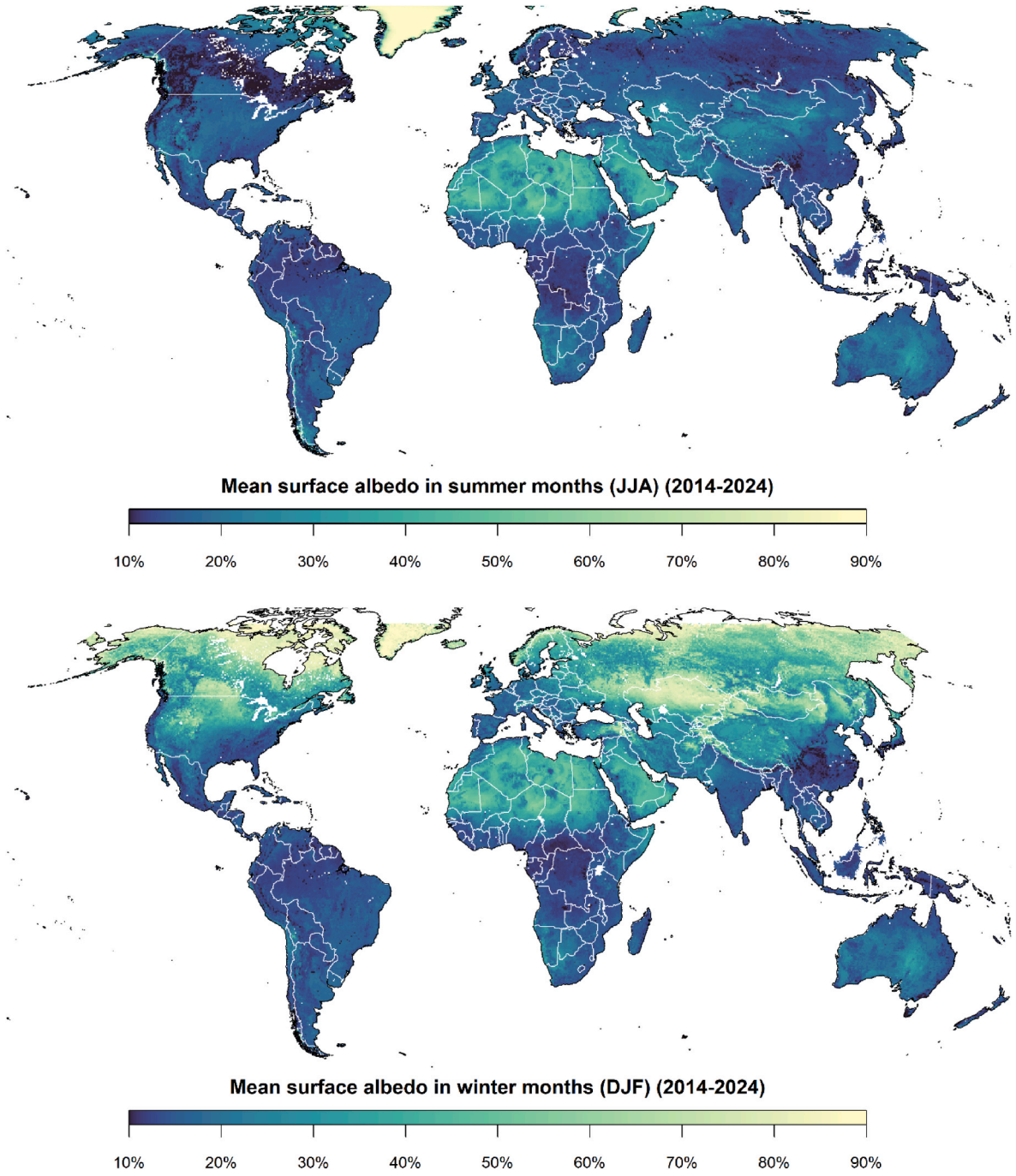


Fig. 18. Global maps of average albedo in summer (top panel) and winter months (bottom panel). Measurements are averaged over the months of June, July and August 2014–2024 for summer, and December, January and February 2014–2024 for winter. Darker colours indicate surfaces with lower light reflection, and bright white areas indicate no data, due to water coverage. Data from Ref. [185].

systems, focusing on the key surface properties of albedo and snow cover, and their influence on solar irradiance, energy generation, and system performance.

5.1. Albedo

Ground reflection, or albedo, plays a key role in Earth's energy balance and climate system. Albedo is the ratio of reflected solar irradiance to total incident irradiance, with 0 meaning total absorption and 1 meaning total reflection [177]. Its value varies widely across different surfaces, and over time due to changes in land cover, such as deforestation, afforestation, urban development, snow falling and melting, ice cover, and building surfaces' reflection in urban areas. Higher albedo surfaces, such as snow-covered hills, sea ice, and deserts reflect a large portion of incident sunlight back into space, and thus have lower temperatures. Conversely, water bodies and forests have darker surfaces which absorb most incoming solar irradiance, and so have low albedo [178].

Global warming is reducing the Earth's albedo, as ice melt replaces reflective surfaces with darker sea or land surface, meaning less incoming irradiance is reflected, thus contributing further to global warming [179]. Fresh snow has a high albedo, reflecting 96–98 % of solar irradiance in the visible and near-UV range and ~80 % across the full spectrum [180,181]. Snow-covered ice sheets reflect 80 % of sunlight, while bare ice reflects only 40 %, or less if there are summer meltwater pools [182]. Cloud cover increases snow albedo by diffusing direct sunlight and altering its spectral distribution. Aerosols like dust and soot can contaminate snow, reducing its reflectivity.

Clouds have varying albedo of 40–90 %, forests typically have 5–15 % albedo, and water can range from 2 to 99 % [179]. Ground albedo depends strongly on wavelength and surface type, with real-world values typically ranging from 10 % in tropical rainforests to approximately 60 % in arid deserts [183]. Fig. 18 illustrates Earth's "black sky albedo", which represents the albedo observed when the sun is directly overhead (local solar noon) across the Earth's surface. Snow-covered polar regions and deserts exhibit the highest albedo year-round, and large seasonal changes can be seen in the tundra regions of Russia and North America. Conversely, tropical rainforest regions and Southeast Asia have the lowest albedo [184].

The increased reflection from higher albedo surfaces increases the insolation incident on solar modules, leading to increased energy generation [186]. This particularly increases generation during times of low solar zenith angle, leading to increased energy generation during peak demand periods in the early morning or early evening [187]. Higher albedo surfaces also have a cooling effect by reflecting sunlight, lowering the operating temperature of PV modules, increasing efficiency and lifetime [188,189].

5.2. Snow cover

Snowfall significantly affects solar PV modules, especially in regions with extended periods of snow coverage including Canada, Russia, and northern US states. Snow cover has complex effects on PV generation due to the interaction of snow lying on the modules and reflected light from surrounding snow-covered surfaces [190]. Although solar irradiance can penetrate through snow [191], modules receive markedly lower irradiance with increasing snow depth, lowering power output [192]. Several studies have quantified the energy lost to snow accumulation on modules [193–195]. Naturally, there is strong regional variation in the impacts. Energy losses from snow cover in Munich, Germany amount to 0.3–2.7 % [196], whereas in Russia losses exceed 40 % with 4 mm thick snow coverage [192].

Module tilt is the most influential factor in determining energy loss due to snow cover [197,198]. Reducing module tilt from 40° to 30° in Utah, US (a high snowfall area) increased daily output losses by 6–19 % [197], and reducing module tilt from 45° to 0° (lying horizontally) in Michigan, US increased annual energy loss from 5 % to 34 % due to snow coverage [199]. For obstructed systems, yearly energy losses remain at 30–34 %, regardless of tilt angle [199].

Snow accumulation on modules is influenced by temperature and humidity, affecting the duration of snow coverage. Warmer temperatures speed up snow melting, while higher humidity increases the residence time of snow on modules. Snow particles can rebound and slide off the module's surface at temperatures near −3 °C [200,201], but as temperature falls below −3 °C, snow particles begin to accumulate through cohesion [201]. Even snow-covered panels can receive incoming irradiance, and the heat generated by PV modules is sufficient for snow to begin melting [190] at temperatures as low as −3 °C, with a snow depth of 10 cm [202]. Snow melting involves a gradual increase in liquid water content as heat is absorbed, reducing friction in the lower layer causing it to slide off solar modules [203]. Snow shedding is the rapid sliding of snow off a surface, often without melting, when the surface temperature is near 0 °C [204]. Prolonged melting occurs when snow slowly melts from the top to the bottom of the modules, increasing the time the modules are covered, and thus energy losses. Melting followed by shedding combines snow melting from the sides with sliding from top to bottom, forming a layered removal process.

Energy yields can be increased by snow coverage in the surrounding area. A 1 % output increase was observed in tilted modules due to increased albedo [190]. Similarly, wall-mounted modules in Japan had increased productivity due to the sunlight reflection off snow [193]. While some studies recognize this benefit, greater understanding of the effect is still required [190]. Snow removal from PV arrays can reduce cell degradation and snow load stress [205]. Several snow removal methods exist [206], for example hydrodynamic coatings reduce snow and ice accumulation [207], although they do not significantly improve PV system performance.

6. Extreme events

This section discusses the impacts of rare and extreme events like hurricanes, floods, wildfires, solar eclipses, and hailstorms, which can all affect the performance of PV systems [208].

6.1. Wildfires

Climate change is increasing the frequency and scale of wildfires globally [209–211]. Wildfires produce large quantities of aerosols that reduce solar PV performance by blocking sunlight. In California, where solar power provides nearly 20 % of electricity, the extreme wildfires in September 2020 reduced solar energy production by 30 % [212]. Similarly, in June 2023, smoke from Canadian wildfires spread to the Northeast and Midwest US, reducing solar generation by up to 60 % in New England [213], and by 25 % in Mid-Atlantic and Midwestern states [214]. New York was particularly affected, losing ~1.5 GW of solar production between 6 June and 7 June 2023 [214].

Cell technologies are impacted differently by smoke aerosols. Based on spectral analysis of the Black Mountain fire in Canberra, Australia during March 2014, amorphous-Si thin film and gallium arsenide single-junction cells showed the greatest impacts from smoke aerosols [215]. Conversely, mono-crystalline Si, and thin film technologies like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) were least affected, with stronger responses in the near-infrared and infrared ranges [215].

6.2. Hailstorms

As with wildfires, climate change is increasing the severity of hailstorms and expanding the areas of the world affected [216–218]. Hailstorms cause varying degrees of damage, influenced by factors like size, intensity, and kinetic energy [219,220]. Damage includes shattered glass, cell breakage, micro-cracks, cell dysfunction, and structural

deformations [221]. The effect of hailstorms on PV modules depends strongly on the material used for the front layer [222]. When the glass covering fractures, it can directly damage the photoactive material or expose internal components to the environment, leading to chemical or physical deterioration over time [223]. More severe storms, such as pictured in Fig. 19 can end the life of modules, but more minor storms also lead to cumulative damage. Microcracks can lead to sections of cells becoming electrically disconnected, gradually decreasing short-circuit current and increasing series resistance, ultimately leading to hotspots and reduced power output [224,225]. Fig. 19 shows the distinctive convex I-V characteristics of cracked PV modules and its deterioration over time [226].

Modules must withstand 11 impacts from 25 mm hailstones at a velocity of 23 m/s, as required by the IEC 61215 standard for c-Si [228]. Newer flat plate collectors with reinforced glass are designed to be resilient against hail-related damage [223]. Unlike silicon solar cells, thin-film cells are less prone to cracking due to lower strain levels [229]. Traditional PV modules use 3.2 mm thick front glass, but in hail-prone areas, at least 4 mm thickness is recommended to minimize damage [222].

6.3. Hurricanes

Wind speeds can reach over 250 km/h during a hurricane, threatening the structural integrity of solar installations [230]. Strong winds and debris can damage modules, mounts, and wiring, disrupting power generation. Proper design and installation can mitigate some of these risks [231]. Table 2 provides some examples of solar PV systems withstanding major hurricane events.

6.4. Solar eclipse

Solar eclipses temporarily reduce solar irradiance, causing a rapid but short-lived fall in solar power generation. A partial solar eclipse occurred in Prague on 20 March 2015 saw 68 % of the solar disc covered at its peak and caused a 69 % reduction in solar PV production [232]. The North American solar eclipse on 21 August 2017 affected nearly 2000 utility-scale plants and millions of rooftop systems across the US from coast to coast [233]. Fig. 20 illustrates the impact on utility-scale solar PV capacity across the states. Only 17 utility-scale plants, mostly in Oregon, were directly affected by the totality path. However, approximately 4 GW of capacity, primarily in North Carolina and Georgia, experienced more than 90 % coverage of the sun [233].

The 2017 eclipse affected almost all of the country's utility-scale systems. However, this capacity was only 22 GW at the time [234], so this impacted around 2 % of total generating capacity. A subsequent eclipse on 8 April 2024 affected over three times more capacity as shown on the right bar of Fig. 20. Systems in Texas lost more than 90 % of output during the eclipse, and those in California lost approximately half their output [235]. In Texas, state-wide solar PV production fell from 7.2 to 1.5 GW in 40 min, and then rose back to 5.9 GW in a further 40 min: giving ramp rates of −8.5 and + 6.7 GW per hour [236]. This output loss is comparable to several large conventional power stations shutting down simultaneously. Battery storage proved to be an important source of flexibility [237] to balance out the rapid loss of power during the

Table 2
Notable hurricanes and their impact on solar PV installations [230].

Hurricanes	Place and Date	Impact
Hurricane Sandy	New Jersey, 2012	200 modules suffered a minor casting problem due to flooding.
Hurricane Maria	Puerto Rico, 2017	The VA hospital's PV system in San Jose remained functional throughout the storm.
Hurricane Florence	North Carolina, 2018	Many fossil-fuel plants were shut down for months, but the solar facilities resumed operation after a few days.
Hurricane Ian	Eastern Florida, 2022	Babcock Ranch, known as "America's first solar-powered town" was able to maintain power.

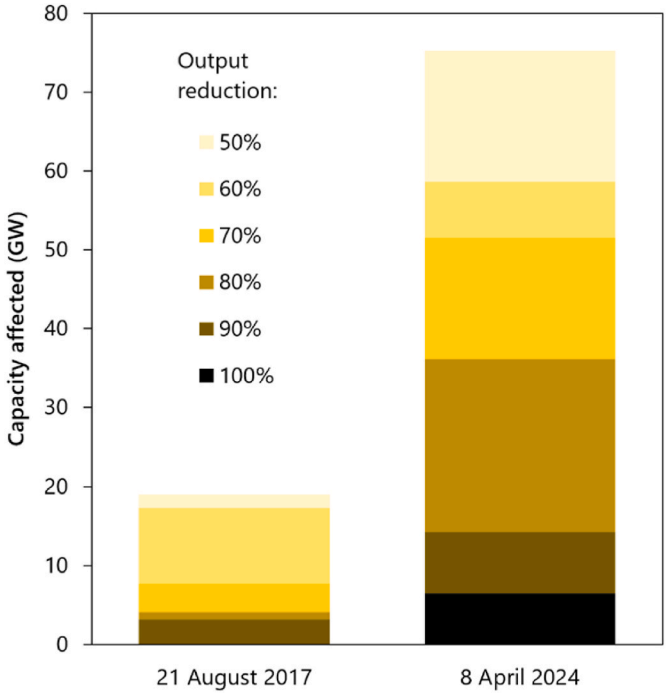


Fig. 20. Utility-scale solar PV capacity in the US affected by solar eclipses in 2017 and 2024. Data from Refs. [234,235].

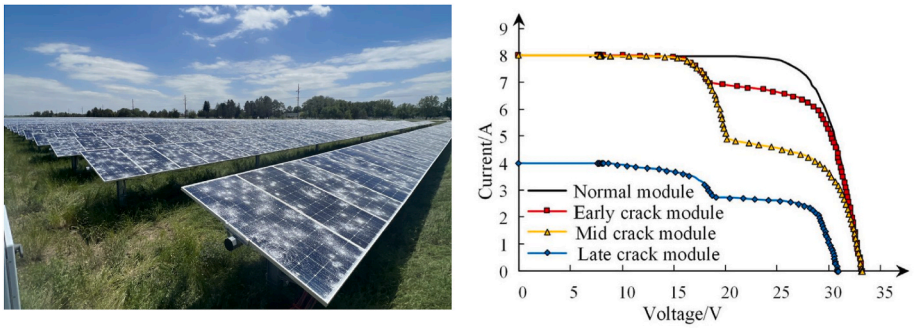


Fig. 19. Damage to PV modules caused by hail in Nebraska, US (left), and the I-V characteristics of cracked PV modules (right). Lines represent the progression of a module's performance over time: 'normal' refers to a module with no cracks, 'early' is 3 months, 'mid' is 6 months, and 'late' is 12 months after cracking occurred. Photo courtesy of GenPro Energy Solutions [227], chart reproduced from Ref. [226].

eclipse.

On 20 April 2023, a hybrid eclipse occurred in Western Australia, focused on the North West Cape peninsula and Barrow Island [238]. This caused significant impacts as Western Australia has a high share of rooftop solar PV systems, and no grid connections to other markets [239]. The impact on state-wide capacity factors is shown in Fig. 21, alongside the impact of the 2017 US eclipse. Should a similar occurrence transpire in regions with more concentrated PV capacity, such as California (42 GW installed) [240], or Japan (83 GW installed) [5], the impact on power system operations could be difficult to manage. The next major eclipses that will affect solar PV production will be in Spain on 12 August 2026, Chile and Argentina on 6 February 2027, North Africa and Middle East countries on 2 August 2027, Indonesia and Australia on 22 July 2028, and Northern China on 1 June 2030 [241].

7. Long-term changes in solar irradiance

Climate change will affect many of the factors that reduce solar PV performance, including increasing humidity and frequency of wildfires and hailstorms as discussed in the previous sections. Primarily, climate change will increase temperatures, with a rapid increase in the exceedance of thresholds such as daily average temperature above 25 °C [245], beyond which cell efficiency falls. Combined with increasing cloud cover, rising temperatures will double the number of summer days with low PV output in the worst affected regions, such as the Arabian Peninsula [246]. In addition, solar irradiance is not constant, and varies over the timescale of decades. Gradual shifts in atmospheric conditions alter global horizontal irradiance (GHI), referred to as 'dimming' and 'brightening' phases [247]. Solar irradiance declined from the 1960s to the 1980s, followed by a partial rebound post-1980s [248,249].

External factors have limited influence. While the Earth's orbit experience changes over long geological timescales, variations over the decades relevant to solar PV productivity are minimal [250]. Similarly, although solar output (total solar irradiance) is observed to fluctuate over decadal timescales, the variation over the 11-year Schwabe cycle is on the order of 0.1 % [251,252], and thus too small to substantially affect productivity. Instead, factors such as water vapor and other radiatively active gases, cloud characteristics, aerosols, and anthropogenic emissions play important roles in determining long-term solar PV performance.

7.1. Water vapor and other radiatively active gases

Water vapor is among the most influential radiative gases present in the Earth's atmosphere [253]. A 10 % rise in atmospheric water vapor concentration reduces GHI by 0.5 % [250]. Since the late 19th century, the concentration of water vapor has risen by an average of 7 % for every degree of warming. This increase creates a feedback loop of further warming, as water vapor is a greenhouse gas that retains heat in the atmosphere [254,255]. The reduction in solar irradiance observed from 1960 to 2000 is an order of magnitude larger than can be attributed to the corresponding increase in water vapor over that period [256]. So, despite water vapor being the gas with the greatest potential to alter solar irradiance, the minor change in its concentration means it is not a primary driver of long-term shifts in irradiance [250].

7.2. Cloud characteristics

Historical cloud cover data primarily comes from manual observations of the sky in the 20th century, with few comprehensive global analyses of observed changes [250]. However, some regional studies exist. For example, solar irradiance on cloudy days decreased by 8 % per decade in Germany between 1964 and 1990, compared to no significant change on clear days [257]. In the US, both an increase in days with cloud cover and cloud optical density were the primary drivers of decreasing solar irradiance between 1960 and 1990 [258].

These findings suggest that changing cloud characteristics strongly influence long-term solar irradiance trends. However, the effects are not universal. China experienced a reduction in cloud cover and an increase in cloudless days from 1954 to 2001, yet solar irradiance decreased

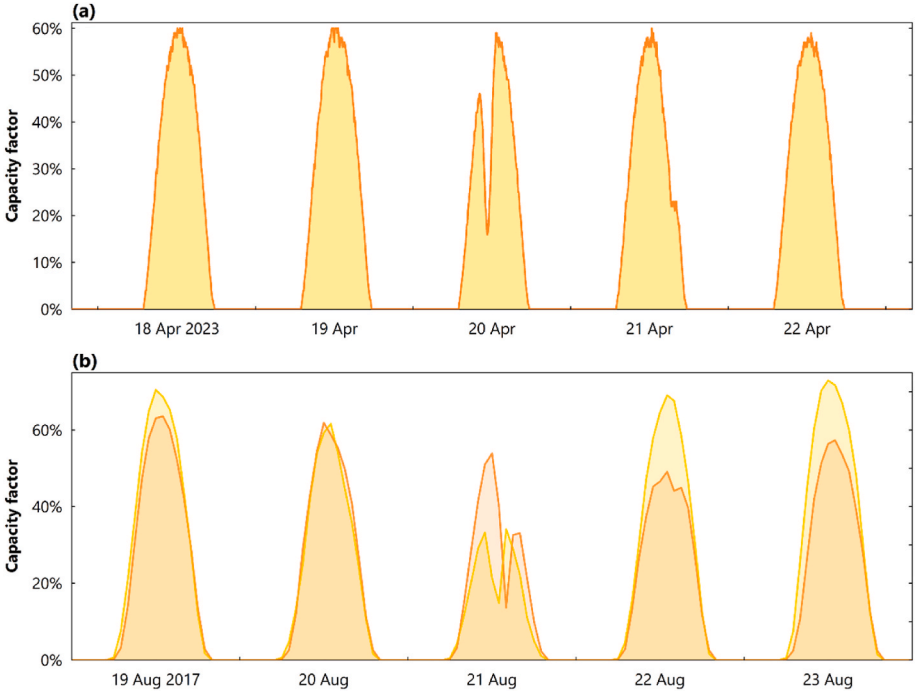


Fig. 21. Average capacity factor of PV systems during total solar eclipses compared to their surrounding days in (a) Western Australia and (b) the United States. (a) shows state-wide capacity factors measured with 5-min resolution, aggregated across Western Australia. Data from APVI [242]. (b) shows the region-wide capacity factors measured with 1-h resolution, aggregated across Central Midwest states in yellow (Kansas, Missouri, Iowa, Illinois, and Indiana) and South-eastern states in orange (Kentucky, Tennessee, North Carolina, South Carolina, and Georgia). Data from PVOutput [243] and SolarEdge [244].

during the same period [259]. Fig. 22 illustrates the heterogeneous long-term changes observed in Low Cloud Cover (LCC) around the world.

7.3. Aerosol effects and anthropogenic emissions

Aerosol load influences the amount of solar irradiance reaching the Earth's surface. Variations in aerosol mass and their optical properties alter the scattering of irradiance, known as the 'direct effect' of aerosols [250]. Furthermore, aerosols contribute to cloud formation by acting as Cloud Condensation Nuclei (CCN): particles that attract water molecules to form clouds [261]; known as the 'indirect effect' of aerosols. The effectiveness of aerosols as CCN depends on their size, chemical composition, and makeup, highlighting the importance of the specific type of aerosol, alongside its mass or concentration [262]. In highly-polluted regions, dense aerosol layers can heat and stabilize the atmosphere which hinders new cloud formation, known as the 'semi--direct effect' of aerosols [250]. This stabilization also reduces surface evaporation, further limiting cloud formation.

Evidence of aerosol effects from the dimming period until the 1980s is largely indirect due to the lack of precise historical aerosol concentration data. Latitudinal data from 1960 to 1990 showed a correlation between emissions from burning fossil fuels and GHI, particularly in areas with high population and industrial activity [249]. Similarly, decreasing GHI in Israel between 1956 and 1987 correlated to the increase in vehicle numbers, despite no significant change in cloud cover [263]. The three-fold increase in black carbon and nine-fold increase in SO_2 emissions in China between 1960 and 2000 was attributed to a dimming of 24 W/m^2, and an 11–15 % reduction in solar PV capacity factors, from a nationwide average of 16.2 %–14.2 % [101].

Since the advent of the satellite era in the 1980s, more accurate aerosol concentration records have clarified the relationship between aerosol load and the observed increase in solar irradiance since the late 20th century [264]. The global decrease in aerosol loading, particularly SO_2 and black carbon emissions falling 0.13 %/yr, has been linked to the rise in solar irradiance of 0.1 %/yr from 1983 to 2001 [265]. Not all changes in aerosol loading are anthropogenic. Aerosol optical thickness has increased during the 21st century in the Arabian Peninsula and parts of the Sahara Desert due to increased dust production [266,267], while decreases have been observed in China and Southwest Asia due to increased rainfall [266,268]. Regions with larger decreases in aerosol concentrations also exhibited the largest increases in solar irradiance. This correlation is supported by several regional studies, including those on fossil fuel emissions in China [259,269], and Atmospheric Brown Clouds in India, predominantly observed during dry seasons [270]. This more direct evidence strongly indicates that aerosol load driving the decadal changes in solar irradiance, and so efforts to improve air quality such as reducing the SO_2 limit on shipping fuel [271] will likely improve solar PV capacity factors in future [264].

8. Conclusions

This review examined the many environmental factors that influence solar PV performance. The individual and combined effects of several key factors must be understood and mitigated to optimize PV output: solar irradiance, temperature, cloud cover, dust and pollutants, snow cover, albedo, and extreme weather events.

Some of the key findings are:

- Solar irradiance is the most significant factor affecting PV performance, with the strongest impact near the equator.
- Higher temperatures reduce PV efficiency, with a typical loss of 0.4–0.5 % loss per 1 °C increase.
- Dust accumulation can reduce efficiency by up to 60 % in desert regions, which is important as these are among the regions with highest potential for PV production.

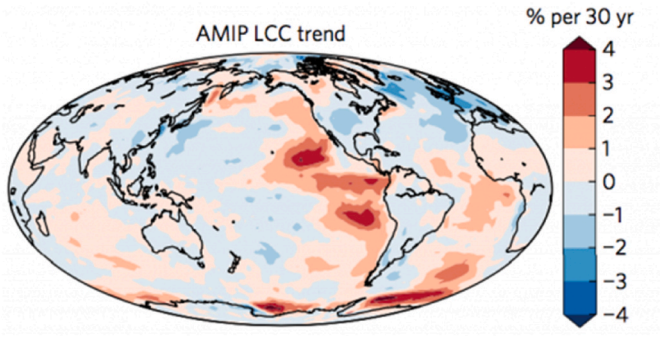


Fig. 22. The global change in low-level cloud cover from 1980 to 2005. Shading depicts increase (red) and decrease (blue) in cloud cover [260].

- Technologies to mitigate these effects through cooling and cleaning panels therefore deserve particular attention to maintain high performance in many world regions.
- Cold regions see mixed effects, with the higher albedo of snow increasing output, but snow coverage of panels reducing it.
- Extreme weather events like hailstorms and wildfires can critically damage PV systems, while wildfire smoke and solar eclipses cause large and highly localized reductions in output.
- Long-term changes in solar radiation, driven by climate change and air pollution will present future challenges for maintaining PV efficiency.

As solar PV installations move beyond the mid-to-high latitudes of the United States, Europe, and China into hotter lower-latitude regions like Africa and Southeast Asia, PV systems will encounter higher dust levels, temperatures, and solar irradiance. Different cell materials, mitigation technologies and operating strategies will be needed to adapt to local environmental conditions, making the findings of this study particularly relevant. Similarly, it is important to recognize the interconnected nature of the above factors that this review uncovered. For example, high temperatures exacerbate the effects of dust accumulation, increasing the need for cleaning and cooling systems in arid and tropical climates. Similarly, while wind can improve cooling, it can also increase dust accumulation and lead to structural challenges.

In conclusion, this review provides a comprehensive understanding of the various environmental factors impacting solar PV output. As solar energy continues to see rapid growth worldwide, this knowledge is essential for modelling and optimizing the performance of solar PV systems across the range of diverse environmental conditions seen around the world. Looking forward, continued research can contribute to improved PV performance under these diverse conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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