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# Enhancement of Ready-Made Silicon Photovoltaic Panels' Field Performance - a Review

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**Abstract:** Photovoltaic (PV) panels have attracted a lot of research interest in the past decade due to their clean and renewable character as an energy source. However, their intrinsic low conversion efficiency has been a major drawback, imposing the need for a huge initial cost of investment. Additionally, due to the low efficiency, PV system installations also require large surface area for panel installation. External factors such as temperature and soiling and shading further reduce the performance of the PV panels operation under real world conditions. Furthermore, the processes used in the fabrication of PV panels do not allow the improvement of panel efficiency once the fabrication is completed. Thus special techniques are required for the modulation of performance on the field. Thermal management schemes and cleaning techniques have been developed to alleviate this existential challenge. Additionally, PV panels operation in the field has been boosted via the improvement of the solar collection methods such as solar trackers, solar concentrators and panel tilt angle. This paper presents a critical comprehensive review of the different PV panel technologies and their field operation challenges as well as the strategies used to enhance the performance of silicon photovoltaic modules (the most attractive single junction PV panels in the market) under field conditions.

**Keywords:** Photovoltaic Panel, PV panel Field Performance, Mono-Crystalline Silicon, Poly-Crystalline Silicon, Amorphous Silicon, Black Silicon Solar Cells, Hybrid A-Si/C-Si Solar Cells

## 1. Introduction

There has been growing interest in all forms of renewable energy in the last decade as researchers seek for alternative energy sources. Amongst the renewable energy, photovoltaic has been the most attractive due to it portability, clean, sustainability, abundance and ease of installation. This interest has been demonstrated the world over, dominated by Asia with China taking lead both in their production and installation (see Figure 3 and Figure 3) [1]. A solar cell is the basic unit that converts sunlight into electrical energy (Figure 1, a basic structure common to most industrial solar cells).

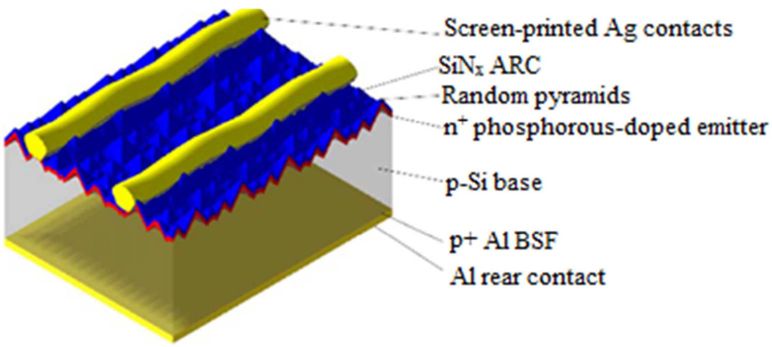


***Figure 1.** The basic structure of solar cell with an Aluminium back surface field (Al-BSF) contact [2].*

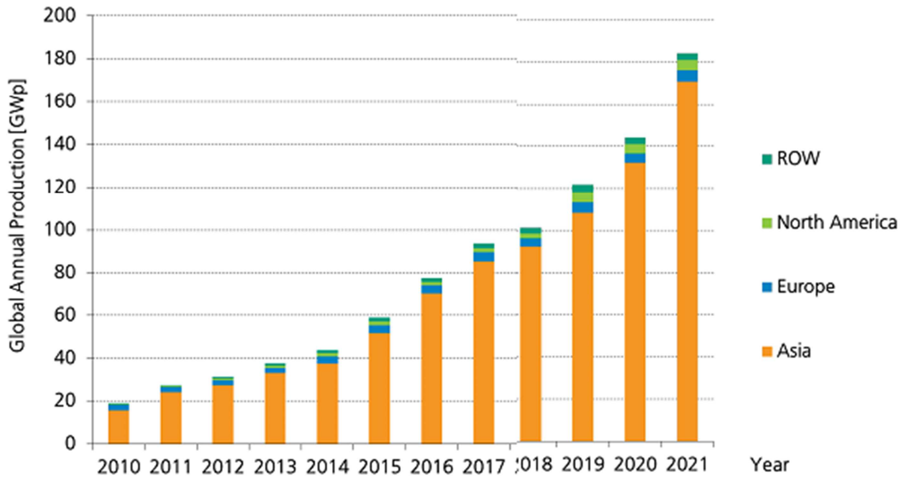


***Figure 2.*** *PV panel production by region 2010 – 2021 [1].*

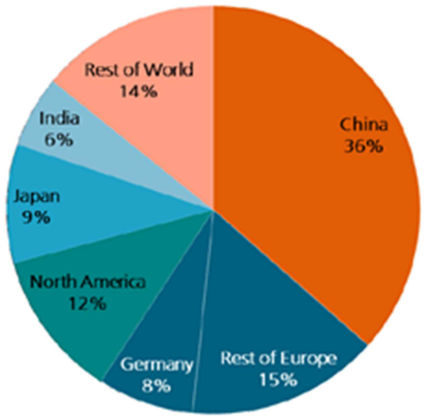


***Figure 3.*** *Global cumulative solar panel installation by region as of the year 2021 [1].*

The silicon solar cell was first demonstrated practically in 1954 by researchers in the Bell laboratory as a power source potential satellite applications [3]. The solar panel is a set of strings of solar cells connected in parallel with a blocking diode in between the strings. In turn, each panel is formed by one or more sub-panels connected in series with a bypass diode [4, 5]. One of the major drawbacks of PV system deployment has been in high initial cost which has a strong dependence on the PV panel cost. On average, in PV systems, the cost of PV panels is still as high as 25% despite the decreasing cost of PV panels [6]. This is usually associated to the low conversion efficiencies of the PV panels which still stands at a maximum of about 20% for mono-crystalline panel, considered to be the most efficient single junction PV technology. Both high initial cost and low efficiency are all dissuading factors for PV system deployment despite the interest. The performance of PV panels in the field is expected to even be lower than nameplate ratings which was measured under standard test conditions (STC) of 1000 $W/m^2$ incident irradiance, panel temperature of 25°C and solar spectrum of AM1.5. Given that these conditions are rarely encountered on the field during system operation, STC ratings are likely to be misrepresentative of the actual field performance which is usually influenced by many different factors [7-11]. In particular, the field operating temperature is far greater than the ambient temperature due heat absorption from the incident solar irradiance and as such reductions in output power are expected [12]. Furthermore, outdoor irradiance is intermittent and rapidly varying throughout the day, further distancing the actual power generated on the field from the predicted values based on STC [13, 14]. Other factors affecting PV panel yield include dust/soil deposition, shading and tilt angle which have adverse effect on the PV panel performance [15-18].

This work provides a comprehensive review of the techniques commonly used to boost the power output of the PV panels operating under real world conditions.

We start by presenting in section 2 the silicon solar cell technology given that it is the most dominant in the market. This is followed by a presentation in section 3 of the environmental impact on the performances of PV systems. Finally, we end this paper by presenting the various techniques used to enhance the PV performance on the field. A summary is presented in Section 5; that include a conclusion and future work.

## 2. Silicon Photovoltaic Technologies

Silicon solar cells remain the most dominant on the market (see Figure 4). The silicon photovoltaic technology can be broadly divided into crystalline and thin film (amorphous) technologies.

### *2.1. Mono-Crystalline and Poly-Crystalline Silicon Solar Cells*

The crystalline photovoltaic panels remain the most popular and attractive PV panel type since the commercialization of the PV panels production. This has been driven in part by the high conversion efficiencies and their long operational lifetime (manufacturers' warranty range is 25 – 30 years before the output power degrades to unacceptable levels) [19]. However, the thin film solar panels are beginning to draw a lot of interest in low cost applications, flexible or bendable applications and also due to their continuous improvement in output conversion efficiency, and also the fact that the crystalline panels are approaching their theoretical limit of 29.05% [20]. The most common design configuration used in the fabrication of crystalline PV panels is made up of different layers (glass front cover, encapsulant, backsheet, Si active layer) in a laminated structure as well internal circuitry (transparent conducting electrodes/interconnects), bypass diodes, junction boxes, frame, cables, and connectors as illustrated by Figure 5; all of these components have the ability to further limit the solar panel efficiency to below the predicted limit making the choice of an appropriate encapsulant material crucial [21-23]. An encapsulant with high transparency, and good thermal conductivity for instance will allow the fast evacuation of heat out of the solar cells resulting to a strong impact on the PV panel performance (fill factor, efficiency and maximum power point) as well as extended lifetime.

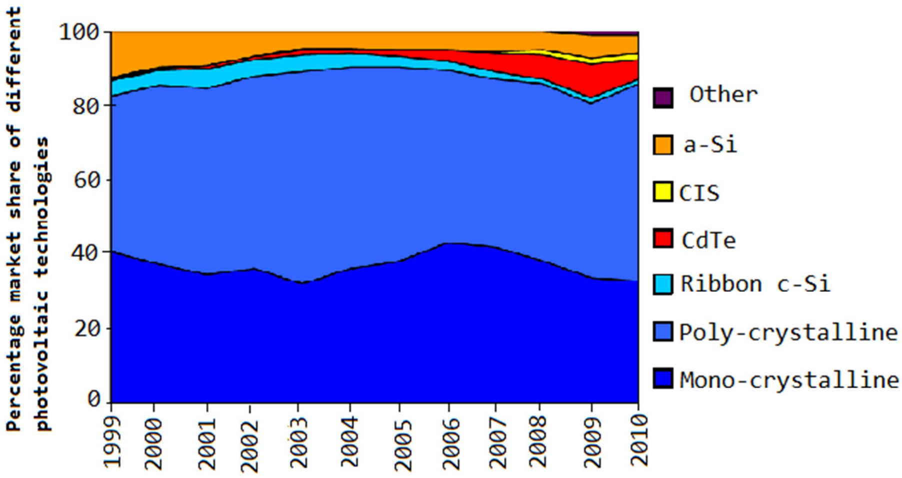


***Figure 4.*** *Market shares of different photovoltaic technologies between 1999 and 2010 [2].*

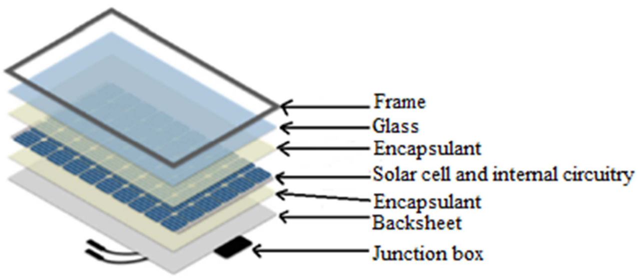


***Figure 5.*** *A common c-Si PV panel configuration adapted from [7].*

The crystalline solar panels are further categorized as mono-crystalline and poly-crystalline solar panels. Mono-crystalline and poly-crystalline silicon differ in physical, chemical and electrical properties due to the differences in manufacturing processes resulting in the variation in cost and efficiency of solar panels obtained [24]. The mono-crystalline silicon solar cell is manufactured by the Czochralski method [25] by slicing high purity single-crystalline silicon (usually having a black appearance) into wafers as compared to the poly-crystalline silicon solar which is made from many fragments by ingot casting technique (appears bluish). The mono-crystalline technology has been reported to be more attractive when compared to the poly-crystalline technology. This is due mainly to the fact the mono-crystalline solar panels exhibit superior conversion efficiency. The main challenge is the fact that the mono-crystalline technology uses rather relatively expensive and high temperature fabrication processes and has reduced flexibility, especially when using thicker wafers which come with improved performance [20, 26]. It is therefore necessary that panels are produced with minimal material waste to guarantee a competitive production cost with an off-set in performance. Reducing the silicon material thickness as a means of reducing material cost degrades photon absorption, degrading the conversion efficiency [20].

### *2.2. Thin Film Silicon Solar Cells*

The thin film silicon solar cells are manufactured using amorphous silicon (a-Si). This silicon type is compatible with low temperature inexpensive deposition techniques. In addition, the technology uses very little semiconductor material given that the films thicknesses are in the micrometers range [23]. Therefore, thin film PV panels are cheaper and are thus suitable for integration in wearable, bendable and flexible applications. They however, suffer from electrical instability issues and low conversion efficiency [21]. The poor electrical instability can be attributed to the presence of a large density of dangling bonds [27]. These effects are often reduced by passivation of the dangling bonds by hydrogen to produce hydrogenated amorphous silicon (a-Si: H) films with improved performance in solar cell applications. Amorphous silicon thin films are commonly deposited by plasma-enhanced chemical vapour deposition (PECVD) method at a moderately low substrate temperatures of 150°C - 300°C (as compared to temperature obtained in crystalline silicon processes) [28]. Another issue encountered by thin film solar cells is the Staebler-Wronski effect, observed during the first few hours of exposure due to light induced current degradation, resulting in reduction in efficiency [29]. However, thin film PV panels have lower temperature coefficient and better output yield under low illumination. Therefore, for PV systems with the same output power rating, Si thin-film are likely to produce higher energy yield per day [23]. Thin film PV panels also possess high surface area to volume ratio leading to the possibility of high heat dissipation further reducing the ramping up in temperature during operation. This would make them suitable candidates in concentrated PV panel systems where higher temperatures are common.

### *2.3. Hybrid Crystalline Silicon/Amorphous Silicon Solar Cells*

The crystalline silicon/ amorphous silicon (c-Si/a-Si) heterojunction solar cells have been report to demonstrate superior efficiency over their individual crystalline silicon and amorphous silicon counterparts [30, 31]. This was first demonstrated in 1992 by SANYO using a junction fabrication temperature of under 200°C [32]. Despite the attractive efficiencies, the main challenge in the fabrication of these type of solar cells is to maintain a low defects density at the a-Si in order to avoid a high carrier recombination.

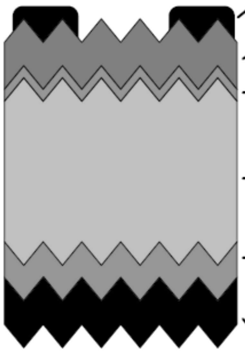


***Figure 6.*** *A sketch of a common structure of a heterojunction solar cell (Fuhs, 2006) [31].*

### *2.4. Black-Silicon (b-Silicon) Photovoltaic Cells*

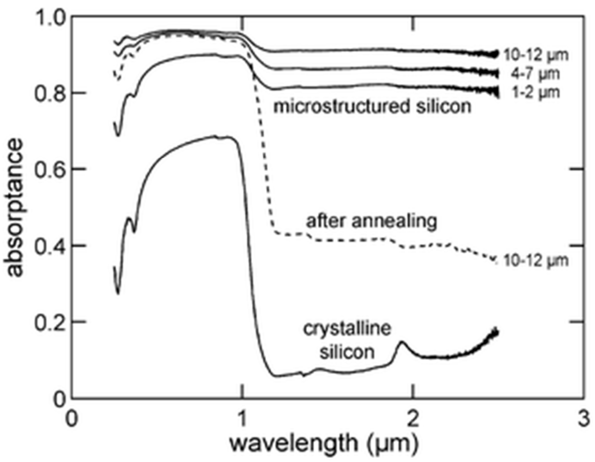


***Figure 7.*** *Absorbance spectra of laser treated BSi samples compared with a standard wafer [33].*

Black silicon has a textured surface, and so has the potential to assist light trapping and resulting to improved conversion efficiency (see Figure 7) [33]. Black-silicon was first produced in 1995 Jansen et al. [34]. Black silicon is characterize by the presence micro- and/or nano-sized structures present on the surface. This contributes to high absorption and reduced reflectivity (no need for antireflection coating) resulting to the dark surface appearance [35]. A major drawback of the use of b-silicon in solar cells fabrication is the requirement for a high temperature (900°C – 1000°C) diffusion process, lead to high thermal budget. In addition, the presence of nanoporous layers in b-Si promotes recombination which has a negative impact on the solar cell performance.

## 3. Effects of Environmental Conditions on the Performance of PV Panels

The performance of PV panels have been seen to be affected by wind, dust and light intensity. The effects of the wind were found to depend strongly on wind incident angle and speed, resulting in the formation of hotspots which have adverse effect on the performance (efficiency) of the PV panel [36, 37]. The wind has the potential of cooling the panels, allowing low temperature operation leading to improved efficiency (see Figure 8).

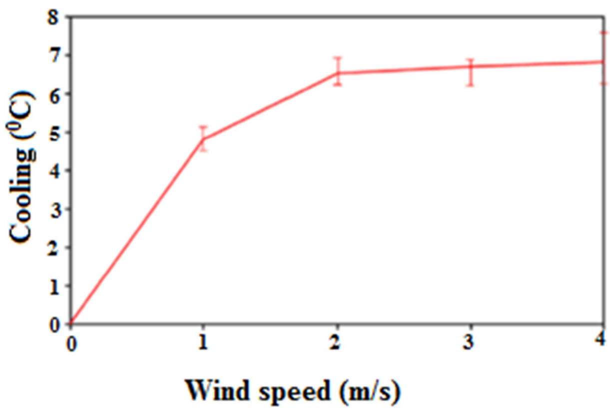


***Figure 8.*** *Dependence of panel temperature on wind speed (adapted from [38]).*

Another environmental condition that has significant effect on the performance of PV panels is the aspect of soiling, commonly caused by dust and other particulate matter in the atmosphere. Soiling is an important consideration when installing PV panels in arid and semi-arid regions due to high dust content in the atmosphere. These regions are usually characterised by low humidity and high solar irradiation suitable for PV applications but soiling and high temperatures are the major issues that must be addressed to achieve efficient operation. The amount of soiling (dust) deposition on the surface of PV panels has been reported to depend strongly on the tilt angle and the wind speed as well as atmospheric humidity. The soiling effect on PV panel performance has been demonstrated to decrease with ambient temperature and tilt angle. Under high humidity with the possibility of droplets (dew) formation, tilt angles have been found to contribute to panel self-cleaning as a result of the trickling of droplets. Vidyanandan showed that dust particle size and density also affect the conversion efficiency (see Figure 11) [39]. It is worth noting that apart from the positive trickling droplet effect resulting from high humidity, humidity also enhance dust accumulation which degrades PV panel performance. High humidity also has the potential to form tiny water droplets on the surface of the panel which can reflect and refract incoming light rays away from the active silicon layer as well as causing delamination and corrosion of the metal contacts and interconnects in the PV system, impacting negatively on the performance [40, 41].

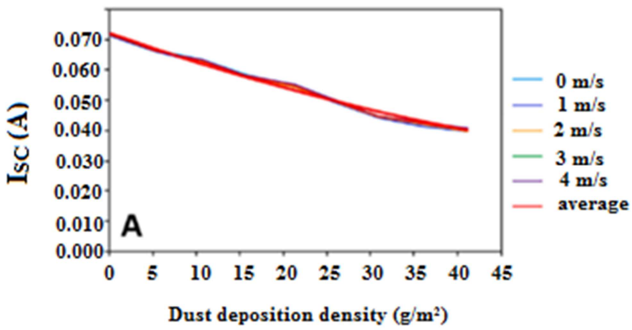


***Figure 9.*** *The variation of short circuit current ($I_{SC}$) with soiling density (adapted from [38]).*

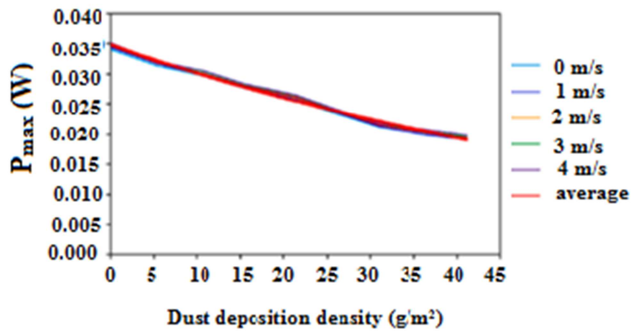


***Figure 10.*** *The variation of maximum output power of the PV panel ($P_{max}$) with soiling density (adapted from [38]).*

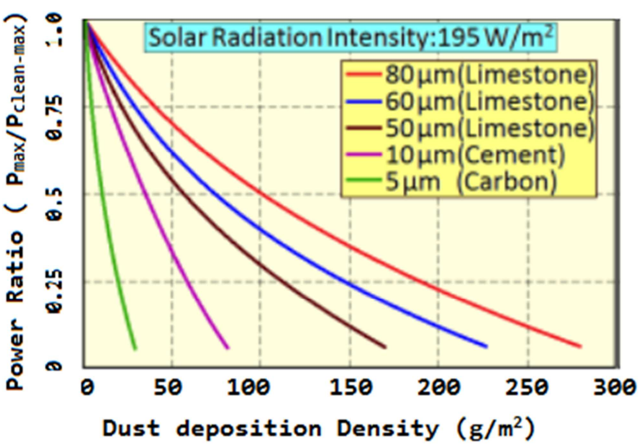


***Figure 11.*** *Impact of dust particle on the PV power output [39].*

In addition, larger dust particles were observed to exhibit less degradation. This can be associated to increased solar radiation percolation with increasing dust particle size as a result of reduction in the packing fraction. Apart from reducing the solar radiation that reaches the solar cells active region in the panel, soiling also has the potential to reduce heat dissipation by the panel. This results in the built-up of thermal energy within the panel and hence increase in panel temperature that have adverse effects on the conversion efficiency and panel effective life. The negative influence of soiling has been observed to manifest mainly via the short circuit current and power output with a weak influence on the open circuit voltage (see Figure 9 and Figure 10) [38, 42, 43].

# 4. Field Performance Improvement Techniques

### *4.1. Use of Radiation Concentrators*

The performance of PV panels on the field has reportedly been improved via the use of solar concentrators such as lenses and reflectors. In this approach, cheap optics and reflectors are used to cut down on the required number of PV panels which have relatively higher cost. V-trough and parabolic reflectors have been reported to produce appreciable improvements in radiation concentration, producing geometric concentration ratios superior to 3.0x resulting to an increase in the PV panel conversion efficiency of about 11% [44, 45]. A major drawback of solar concentrators in PV applications is the increase in solar cell temperature which results in temperature-induced degradations in efficiency and panel effective live. Another drawback of solar concentrators is that they often require sun tracking systems, incurring extra cost in energy and maintenance. A suitable temperature management strategy is also required to keep the PV panels within normal operating cell temperature (NOCT). Amongst the temperature managements schemes, the hybrid solar photovoltaic-thermal (PV-T) approach has been very attractive [46].

### *4.2. Optimum Tilt Angle and Solar Trackers*

The tilt angle of PV panels operation can have significant influence on its output power. Therefore, it is important that the PV panels are installed at the optimum tilt angle to receive maximum solar irradiance. The maximum solar intensity is captured when the panel surface is normal to the incoming solar rays [47]. An efficient approach commonly used to get maximum solar radiation at the PV panel surface is by using the solar tracking systems which follow the path of the sun as the earth rotates and revolves around the Sun [48, 49]. This maximizes the captured solar energy, resulting to reduction in the number of PV panels required for the given system as well as increasing PV panel integration into the grid with the potential of lowering greenhouse emissions [4, 50]. The major issue using trackers is that they are complex, expensive, requiring repair and maintenance as well as energy to run the additional system. The dual-axis tracker has been reported to improve system power output by up to 32% while the less costly vertical tracker with power improvement of 23% has been demonstrated to be economically more attractive [51, 52]. Therefore, for small and low-cost PV systems, fixed PV installations with an optimum tilt angle are still very attractive [49]. The optimum tilt angle has been reported to depend on the latitude and climatic conditions [53]. In addition to the tilt angle, the altitude (β) and azimuthal ($\phi_s$) angles are other parameters required to define the exact orientation that produces optimum solar absorption (see Figure 12) [54, 55]. This is due to the fact that the altitude and azimuthal angles affect the solar path which in turn exhibits an inverse square law with solar irradiation intensity (given that, the output power of a PV panel has a strong dependence on incident irradiation). In addition to the tilt angle influence on the received irradiance, it also affects dust accumulation on panel surface. This is due to the fact that tilt angle affects the magnitude of the effective panel surface area exposed to dust, particle adhesion as well as it influence on runoff of rain and precipitation drops, which natural panel cleaning agents [56].

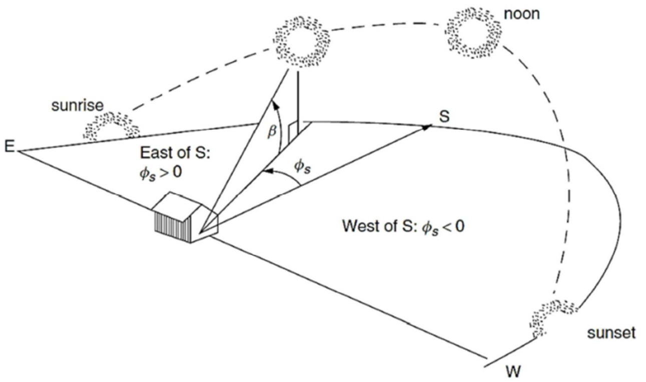


*Figure 12. The dependence of the Sun's trajectory on the solar altitude (β) and the azimuthal angle ($\phi_s$).*

### 4.3. Optimum Tilt Angle and Solar Trackers

Some of the common techniques that have been investigated for cooling of PV panels include: water cooling (by flowing, immersion or spraying), use of phase change materials, natural air convection and forced air convection, use of heat exchangers, heat sink etc. [57-61]. The cleaning methods can be broadly grouped as active and passive cooling techniques. The active cooling methods are generally more efficient but incurs a higher operational cost. Therefore, passive cooling methods are commonly used in small and low-cost PV installations. For most silicon PV panels, the maximum allowable temperature (MAT) is about 45°C [62]. Thus, any cooling method with capability to maintain the PV temperature below 45°C has the potential to improve the conversion efficiency of the PV system [63].

### 4.4. PV Panel Cleaning

The accumulation of dust, snow, bird droppings and other particulate matter have been found to degrade the PV panel conversion efficiency by up to 20% at dust deposition thicknesses between 2 and 3 µm [64, 65]. In many instances, the efficiency can be restored by panel cleaning using one or a combination of the following commonly used techniques which could be manual or automatic via vacuum, electrostatic precipitator, air-blowing, water-blowing, ultrasonic vibrations as well as self-cleaning coating techniques [66]. The downside of panel cleaning is that if not treated with care, this can cause physical/chemical scratches while scrubbing. These scratches can have negative impact on the photon absorption and hence conversion efficiency as well as acceleration of panel life degradation. Regular cleaning of solar panels apart enhancing solar radiation absorption via the removal of accumulated dust, dirt, and debris, can also help in the early identification of potential issues before they become critical.

## 5. Conclusion

From the review of the different silicon solar cell technologies, it can be observed that the cost and efficiency of solar panels in the technologies studied is approaching it absolute minimum while efficiency is attaining its maximum limit. This means that further improvement in the solar cell output performance in the future shall strongly depend on the modulation of field operating conditions. It is observed that the use of inexpensive and less complex methods would be prominent amongst such future research. The selection of an optimum tilt angle and regular maintenance through cleaning shall also remain an attractive pathway for optimum photovoltaic output in the different technologies.

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