Towards improving the performance of solar photovoltaic energy system: A review

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Abstract. Performance of solar PV energy system is affected by many factors like solar radiation intensity, solar radiation geometry, temperature, wind speed and direction, relative humidity, dust, etc. Many researchers have been working on the effect of temperature on solar PV cell efficiency and have reported that increased cell temperature tends to reduce the efficiency of solar PV cell. Solar PV cell temperature also considerably deteriorates the mechanical properties of backsheet of solar PV panel. This paper reviews the various attempts to improve the performance of crystalline silicon solar photovoltaic (PV) system. Performance of a solar PV panel when exposed to hot and dry climate is different from performance of similar solar PV panel in cold climate. From solar beam radiation, light is a desired component whereas heat is not. Therefore many researchers have reported cooling techniques for Solar PV system. However, backsheet material of solar PV panel is one of the factors affecting the solar PV panel efficiency which is pulling the attention of many researchers for performance enhancement of Solar PV system. Solar PV cells using Perovskite material have emerged as one of next generation of photovoltaic technologies having capability of significant enhancement in solar cell efficiency.

1. Introduction

Crystalline Silicon Photovoltaic (PV) cell works on photovoltaic effect. Solar beam radiation contains photo energy (light) as well as heat energy. Out of these two, light in the form of beam radiation is the most desired while heat energy is least desired since crystalline silicon PV module is considerably affected by its temperature [1]. Increased temperature of solar PV cell reduces its efficiency. Heat energy received by a silicon wafer is transferred to its backsheet which should be dissipated as quickly as possible. For a solar PV module, it is required to have an electrically insulating backsheet to hold silicon wafers. An electrically insulating material is usually a bad conductor of heat as well. Therefore heat is required to be dissipated from solar PV cell as faster as possible. For this, backsheet of a solar panel is one of the most important factors responsible for dissipation of heat from solar PV module. Thermal conductivity of the backsheet plays an important role in dissipating the heat from backsheet of solar PV module. Many materials used as backsheet for silicon wafers in solar PV modules are not good conductors of heat and thus heat is dissipated slowly resulting in poor efficiency. Apart from temperature other climatic factors such as relative humidity, wind speed and direction, dust, rain, etc. also considerably affect the performance of the crystalline solar PV energy system.
2. Why crystalline silicon solar PV cell?
A simple solar cell is a p-n junction diode. The efficiency of a solar cell depends on the band gap of the material. Bandgap (\(E_g = 1.1 \text{ eV}\)) of silicon falls in the visible spectrum making it capable of absorbing light received from solar radiation resulting in the flow of photocurrent. It has nearly an ideal bandgap for solar cell efficiency. Physics of Silicon is a well-studied and explained by many researchers. Appropriate doping techniques are also available so as to introduce the carrier transport asymmetry. Silicon is a semiconductor and semiconductors have properties that fall between a conductor and an insulator. Silicon is one of the most abundantly available elements in the earth's crust. Solar photovoltaic panels made from silicon are available in various forms such as amorphous, polycrystalline, monocrystalline, etc. Other materials for solar photovoltaic panels are Copper Indium Gallium Selenide (CIGS), Copper Indium Diselenide (CIS), Cadmium Telluride (CdTe), Gallium Arsenide (GaAs), etc. Cost per unit power for CdTe PV system is lower than that of Silicon but CdTe PV cells exhibit lower efficiency. This makes Silicon a better material for fabricating PV cells. Apart from better efficiency to cost ratio, abundant availability and ability to withstand in diverse climatic conditions make silicon a very popular material for solar PV cells. These are the reasons why solar photovoltaic applications utilize solar PV panels having silicon PV cells. As per the reports International Technology Road Map for Photovoltaic (ITRPV) in 2015 nearly 90% of solar PV applications used crystalline silicon (c-Si) PV cells against 10% share of thin film solar cells. It is further predicted that by 2017 share of thin film technologies to drop down to 7% only [2].

3. Effect of temperature on solar cell performance
Solar PV system exhibits the panel efficiency in the range of 15-18% which is already lower and raised temperature tends to decrease it. Every \(1^\circ\text{C}\) rise in temperature usually causes the 0.06% reduction in the efficiency of the solar cell [3]. Peng et al. [4] investigated the practical effects of solar PV surface temperature on output performance and reported that Provision of cooling function on the back of solar PV panel increased efficiency of solar PV module almost by 47%. Apart from temperature and before selecting a site for installation, wind direction and wind speed frequencies are also need to be taken into account so that air can carry as much heat as possible [5]. Khenfer et al. [6] reported an increase of 3% in the voltage generated by a PV panel by making a provision of low power fan cooling to a solar PV system. Owing to increase in solar cell temperature, reverse saturation current increases with temperature so open circuit voltage decreases resulting in decreased efficiency [7].

![Figure 1. Efficiency Vs Module Temperature (without cooling) [3].](image)

Along with temperature some other factors like rain, snowfall, dust, relative humidity, etc. also cause the decrease in efficiency by offering a resistance to either light entering the solar cell or heat dissipation from solar cell. Figure 1 shows that efficiency of the solar cell increases with irradiation;
however it decreases with increase in solar cell temperature for the same radiation [3]. Andrews et al. [8] commissioned and monitored a solar PV energy system over two winters and reported losses in overall output of solar PV system due to snowfall [8]. Hot and dry climate does not only result in decreased power output of solar PV system but it also causes the defects leading to failure of a crystalline silicon solar PV panel and exergy losses resulting in lower output [9,10]. Solar PV system performance is season dependent as well. Figure 2 shows some observed defects such as delamination, discoloration of the encapsulant, corrosion, discoloration of the metal parts, cracks in SPV cells, etc. in SPV module subject to hot and dry climate in Algeria. Vasishht et al. [11] assessed the performance of solar photovoltaic installations for different seasons in Bangalore (India) and reported a difference in efficiency reduction per degree rise in temperature for different seasons. They observed that efficiency reduces per degree rise in temperature by 0.08% in summer, 0.04% in monsoon and by 0.06% in post-monsoon season. Benghanem et al. [12] also investigated the behavior of a solar PV system in hot climate and reported a decrease of 0.5% in efficiency for a unit rise in temperature. Effect of geographical location and other climatic factors such as relative humidity, variable irradiance, wind flow patterns, etc. have also been addressed by some researchers [13, 14].

![Figure 2. Observed defects in SPV module subject to hot and dry climate in Algeria [9].](image)

4. Cooling techniques for enhanced heat dissipation
As reported by many researchers, increased solar cell temperature is least desired in solar PV energy system. Therefore lot of investigation is being carried out in the field of cooling techniques for solar PV energy systems in order to increase the heat dissipation rate from the solar PV panel to the atmosphere. Siecker et al. [15] have reviewed various methods used to reduce solar PV module temperature and reported that proper cooling of solar PV systems improves overall efficiency, reduces rate of cell degradation, maximizes life span of the PV module. However an emphasis needs to be given to natural cooling techniques so as to reduce the size, cost and maintenance of the system. Solar PV system cooled using water vaporizing observed 1^\circ C reduction in temperature resulted in an increase of 0.5% in efficiency, but system becomes 10-15% expensive than conventional solar PV system without cooling [16]. In order to control the temperature of solar PV panel during its operation, Chandrasekar et al. [17] developed a passive thermal regulation technique with heat spreaders with cotton wicks. They observed a significant decrease of 12% in the temperature resulting in 14% increase in electrical yield. Ebaid et al. [18] investigated the performance of 20 kW solar PV system experimentally using two different nanofluids TiO_2 and Al_2O_3 in water mixed with other mixtures and
reported that solar PV system was least efficient without cooling and most efficient with nanofluid mixed with water cooling. In one more cooling technique, thorough holes were drilled in solar PV panel for causing the hot boundary layer to rise and go through the holes by thermo-syphon effect ensuring the cooling of solar PV panel. For a solar PV panel area of 0.26 m², 6 holes were drilled by Abd-Elhady et al. [19] that gave a drop of 16°C (i.e. from 70 to 54°C) in temperature. However, another 6 holes for the same area resulted in further temperature drop of just 3°C. Many researchers experimentally investigated and reviewed different techniques like passive cooling, using high thermal conducting backsheet, real time temperature regulation using active cooling, etc. [20-22]. In passive cooling of solar PV panel, use of phase change materials has yielded a significant temperature drop resulting in improved efficiency. However, higher cost of phase change material restricts many researchers to consider this as a cooling medium in solar PV applications. Nižetić et al. [21] have considered pork fat as a cheaper phase change material. They have compared two PV systems using numerical model out of which one was cooled with convectional organic PCM while other one used pork fat as a novel PCM. Performances of both the systems haven’t shown much significant variation. They reported that though pork fat is a potential PCM for solar PV cooling but its cost is still not economical. Müslüm et al. [22] also developed a numerical model for analyzing performance improvement in PCM cooled solar PV system. They also reported a drop of 10.26°C in temperature and up to 3.73% increase in efficiency. As far as cost of PCM is concerned, they also reported that significant drop in PCM cost is required to justify the economic viability of PCM cooled solar PV system. Sajan Preet [23] has reviewed the photovoltaic thermal management systems based on water and phase change material. He has reviewed the water based hybrid photovoltaic-thermal systems (PV/T) proposing heat dissipation of solar PV system as heat source of solar thermal systems. Many researchers have also used phase change materials for performance improvement of solar PV/T systems Thermal management of solar PV/T systems using phase change materials is being considered by many researchers but dearer cost and bulkiness of overall system are the main issues to be looked after. A provision of suitable heat path for heat dissipation in the frame of a solar PV module also influences the overall performance of solar PV energy system.

5. Role of backsheet material
Different cooling techniques for active and passive thermal regulation of solar PV modules have shown decrease in solar PV cell temperature resulting in overall performance improvement of solar PV energy system. But implementing cooling technique to a solar PV system bloats the cost of the system. On the other hand, feasibility of providing a particular cooling technique for a large scale solar PV energy system will make a system bulky as well as dearer. A natural cooling has always been a promising alternative to driven one. This is achieved by either modifying the structure of solar PV panel or changing the materials responsible for heat accumulation and dissipation. In this regard, role of backsheet material and its properties have been addressed by very few researchers. One of the reasons behind less address to the backsheet material is a requirement of a certain material which is electrically bad conductor but thermally good conductor. But a material which is bad conductor of heat is usually a bad conductor of heat also.

Typically used backsheet materials are Polyvinyl Fluoride (PVF) also known as Tedlar, Tedlar Polyester Tedlar (TPT), Polytetrafluoroethylene (PTFE), Ethylene Vinyl Acetate (EVA), etc. Most of the materials used as backsheet for silicon wafers in solar PV modules are not good conductors of heat and thus heat gets dissipated slowly resulting in poor efficiency. If the heat dissipation rate of backsheet of the solar PV module is increased, improved performance solar PV module will be observed. Kim et al. [24] used a highly thermal conducting back sheet with graphite and aluminium film and investigated that final temperature of the solar PV panel decreased and Voc increased as compared to that of reference solar PV panel without graphite and aluminium film. Kim et al. [25] used Aluminum nitride and boron nitride surface as thermal conducting filler in conjunction with a poly-vinylidene fluoride matrix as high thermal conductivity material for backsheet of solar cell. As a result, ceramic fillers created heat flow paths and significant increase in thermal conductivity has been
observed. However a material with improved thermal conductivity must not compromise with other properties such as strength, durability, resistance to moisture, etc. Therefore it is crucial to get new material characterized. Elbreki et al. [26] reviewed the work of many researchers who used combined solar photovoltaic-thermal (PV/T) systems to lower the adverse effects of temperature on solar PV panel. However many researchers reported lower electrical efficiency of solar PV system and lower thermal efficiency of solar thermal system in combined solar PV/T system. Along with the backsheet material of the solar PV panel, analysis of thermal profiles at the backside of solar PV panel is also equally important. Temperature distribution pattern is one of the important aspects to be considered for enhancing heat dissipation rate from the backsheet of solar panel. Nižetić et al. [27] investigated the thermal profile of backside of solar PV panel and reported its impact on solar PV panel performance. They further proposed a requirement of redesigning backside surface of solar PV panel to ensure uniform temperature distribution which can result in improved efficiency.

6. Perovskite- A promising SPV material

Approaches pertaining to performance enhancement of a solar PV system using Perovskite (ABX₃) as a solar PV material with a key focus on its thermo-mechanical properties are being considered by researchers these days. Perovskite basically refers to an absorber material. Perovskite solar cells are emerging as promising element of photovoltaic system owing to its higher power conversion efficiency (above 20%). Perovskite is easy to process and it also shows very optical and electronic properties [28]. However Perovskite is preferable considered for the configuration of tandem cell. Researcher’s community working in the area of crystalline silicon solar PV cells and thin film solar cells are also showing their interest in Perovskite solar PV cells (PSV) owing to its higher electrical efficiency as reported by many. Typically used perovskites are based on organic-inorganic lead perovskites with polycrystalline structure. This material has good optical absorption, higher mobility of electron and hole, good diffusion lengths, better tolerance to structural defects, etc. making it able to pull attraction of solar PV cell research community [29].

Perovskite solar cells have shown an astonishing performance improvement in a small tenure of a decade. Major focus has been and is being put on enhancing the electrical efficiency. However, low research has been carried out as far as stability and durability of perovskite solar cells is concerned. In case of crystalline silicon solar PV cells, a life of approximately 20 years is usually expected. Very fewer studies investigating stability and durability of PSVs have been reported till date. Asghar et al. [30] reviewed the device stability of PSVs and reported that PSVs showing higher performance closer to that of crystalline solar PV cell tend to degrade quickly. Higher electrical efficiency can’t be the only advantage to comment that perovskite solar cells are better than crystalline solar PV cells. Its durability should also be at par with that of crystalline solar PV cell. A Barrier to commercialization of perovskite solar cells is its poor stability. When a PSV is exposed to a moist environment, it exhibits instability. Other issues that affect the stability of PSVs are UV-light, temperature, encapsulation techniques, testing protocols, etc. [31]. Proper encapsulation will be a vital development to ensure the stability of PSVs. It will also tackle with the issue of moisture affecting the stability. Such an approach will surely lead to the goal of commercialization of perovskite solar PV cells.

7. Discussions

After reviewing the attempts of various researchers to improve the overall performance of solar PV system addressing the temperature related issues, it is inferred that natural cooling should be preferred over forced cooling. Although many artificial cooling techniques for solar PV systems have shown good results; their implementation on large scale solar PV plants have been tried by very few. Usually, more cooling of solar PV systems is required in hot and dry climates where scarcity of water is a major concern. Therefore, cooling using water spray is not feasible in hot and dry climates. Other forced convection systems increase overall cost and size of the system. Use of phase change materials is also considered by many researchers simultaneously stating that high cost of PCMs limits their utility in cooling of solar PV systems. Enhanced heat dissipation (naturally) through backside of solar
PV panel is a promising solution as it’s absolutely feasible for any sized solar PV plant. Therefore, developing a high thermal conducting backsheet material will be a vital milestone for solar PV system performance improvement. Combination of high thermal conducting backsheet and perovskite material for solar cell can result in an efficient solar PV system.

8. Conclusions
Crystalline silicon is a popular solar PV material due to its availability, cost, durability, efficiency, etc. and hence it is found in nearly 90% of solar PV applications. Increased solar PV cell temperature due to poor heat dissipation rate has been among of the major parameters affecting the efficiency of the solar PV system. For enhanced heat dissipation, many researchers have investigated various cooling techniques and reported that drop in solar PV cell temperature resulted in improved system efficiency. For cooling of solar PV panels, researchers have considered water spraying, heat spreading using cotton wicks, phase change materials, drilled solar PV panels, forced convection, etc. Although, cooling techniques ensure performance improvement, their implementation results in increased system cost, operational cost, maintenance, size, etc. Some cooling techniques showed very good results in laboratory but they haven’t been tested for a large scale solar PV power system. Therefore an emphasis has been given to natural cooling that does not considerably increase the cost and size of the system but improves the performance. For better thermal management of solar PV system, backsheet material plays a vital role. Characterization of a certain material which is a good conductor of heat but poor conductor of electricity can be a promising natural cooling medium for solar PV system. Perovskite ABX₃ has emerged as a good substitute to crystalline silicon as a PV material showing higher electrical efficiency. However, it is not yet as durable and stable as silicon. From the review of various articles pertaining to PV material, cooling techniques, backsheet materials, hybrid systems, etc. a combination of highly thermal conducting material (after characterization) and perovskite ABX₃ (after ensuring stability and durability) can prove a solar PV system with improved overall performance.

Authors believe that the presented review can be used by researchers and engineers to explore new and innovative ways of cooling of solar PV system by enhanced heat dissipation rate with an emphasis on natural cooling to improve its efficiency.

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