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THERMAL MANAGEMENT OF SOLAR PHOTOVOLTAIC PANEL (PV) FOR PERFORMANCE ENHANCEMENT :A REVIEW

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Abstract-

Thermal management of solar photovoltaic panel is critical issue in operation solar photovoltaic system for generation of electricity. The efficiency of solar photovoltaic system is around 10 to 25 %. Higher operating temperature results in reduction in efficiency, overall system performance. This review paper highlights the main challenges encountered within the solar photovoltaic system and address the significance of temperature influence on performance of solar photovoltaic panel, various cooling techniques are discussed to optimize the system performance operating in practical condition and to harness the thermal energy waste from solar photovoltaic panel for improving conversion efficiency. Several research papers are reviewed and based on their focus, contribution and the type of technology used to achieve the cooling of photovoltaic panels are discussed.

Keywords—thermal management, operating temperature, efficiency, cooling technique.

INTRODUCTION

The electrical conversion efficiency of PV cell is significantly affected due to the surface temperature of the PV panel [1]. Solar energy is one of the most widely exploited energy sources that can be utilized in various applications such as, thermal management using thermal collectors or electricity generation through special optical solar cells, also known as Photovoltaic (PV) cells. PV cells are semiconductor devices that have the ability to convert the energy available in both dispersed and concentrated solar radiation into direct current (DC) electricity. Conversion of solar energy into electricity through PV cells is achievable at different efficiency ratings, varying between 10-25% and determined primarily by the type of semiconductor material from which the cells are made.

PV technologies have been adopted in many regions worldwide, as solar energy is abundant on the earth's surface. PV systems offer wide range of applications from direct power supply for appliances to large power stations feeding electricity into the grid and serving large communities. Although, PV systems have been commercially available and widely operated for many years, certain barriers stand towards the widespread application of this technology [2].

Solar PV cells are the primary element of PV systems, and mainly are semiconductor devices that can convert solar radiation into DC electricity when exposed to sunlight. Such optical cell consists of a P-N junction formed on a thin light sensitive material primarily silicon Si. The P-N junction of the cell is formed by doping silicon wafer with impurities, hence creating two layers with different electrical properties. The physical process through which solar cells convert solar radiation into electricity is known as the "Photovoltaic Effect". Photons available in sunlight makes electricity generation possible using PV cells. The basic process of electricity generation when a PV cell is exposed to sunlight is shown in figure below.

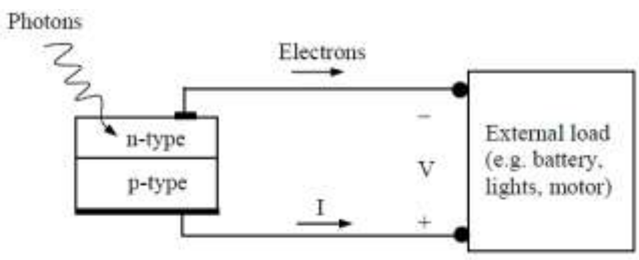

Fig. 1. PV Electricity Generation Process

As sufficient photon energy is absorbed by a PV cell, electrons migrate from the negative layer to the positive layer of the cell, resulting in potential difference across the P-N junction, and therefore, current flow to the load through an external circuit.

Photovoltaic (PV) electricity generation is a method of transforming sunlight into electricity with the help of semiconductor materials that show the photovoltaic effect. Photovoltaic systems are composed of a number of solar cells to supply serviceable solar power. Power generation from solar PV is a clean and sustainable tool, which depends upon the planet's most ample and widely spread renewable energy source of the sun. Straight transformation of sunlight to electricity takes place without any moving parts or environmental releases through the process. This technology is well recognised, as photovoltaic systems have now been used for over fifty years both for stand-alone uses, and grid-connected installations. It is well known that the efficiency of photovoltaic solar cells declines with an increase in temperature. Earlier theoretical studies [3–7] have shown the efficiency decrease which is expected, but the carrier transport mechanism put a significant effect on the actual temperature coefficient of the efficiency, and in different cases could differ significantly depending on the ambient conditions; the effects of recombination generally increase the efficiency deviation with temperature.

PARAMETER AFFECT THE PERFORMANCE OF SOLAR PHOTOVOLTAIC (PV) PANEL

Effect of Temperature

PV cells absorb up to 80% of the incident solar radiation, however, the proportion of converted incident energy into electricity depends on the conversion efficiency of the PV cell technology [8]. The remainder energy is dissipated as heat and the PV module can reach temperatures as high as 40 °C above ambient. This is due to the fact that PV cells convert a certain wavelength of the incoming irradiation that contributes to the direct conversion of light into electricity, while the rest is dissipated as heat. Shortwave radiation can be converted to electricity using photovoltaic (PV) technology. However, the photoelectric conversion efficiency is only 5–20%.

Limited Conversion Efficiency

The photoelectric conversion efficiency of commercially available single junction solar cells ranges between 10-25% under optimum operating conditions. The efficiency is mainly determined by the semiconductor material from which the cell is made.

However, PV systems do not operate under standard conditions, thus variation of operating temperatures limit the efficiency of PV systems [9]. Such limited efficiency is associated with the band-gap energy of the semiconductor material [10].

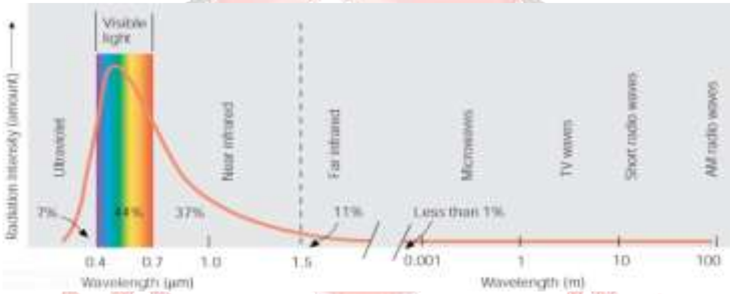

Fig. 2. Solar radiation spectrum

Crystalline silicon PV cells can utilize the entire visible spectrum and some part of the infrared spectrum. Nonetheless, the energy of the infrared spectrum, as well as the longer wavelength radiation are not sufficient to excite electrons in the semiconductor material to cause current flow. Similarly, higher energy radiation spectrum which is capable of producing current flow; is unusable. Consequently, radiation with high and low energies is ineffective for electricity generation, and instead is dissipated at the cell as thermal energy, accounting for losses above 50% of the absorbed light The PV cell performance decreases with increasing temperatures, fundamentally owing to increased intrinsic carrier concentrations which tend to increase the dark saturation current of the p-n junction Reduction in band-gap due to high doping also serves to increase the intrinsic carrier concentration The increase in dark saturation current causes the open-circuit voltage to decrease linearly, which for silicon at 300K correspond to about 2.3 mV/°C [11]. For crystalline silicon PV cells, a drop in the electrical power output of about 0.2–0.5% was reported for every 1°C rise in the PV module temperature primarily due to the temperature dependence of the open-circuit voltage of the cell [12].

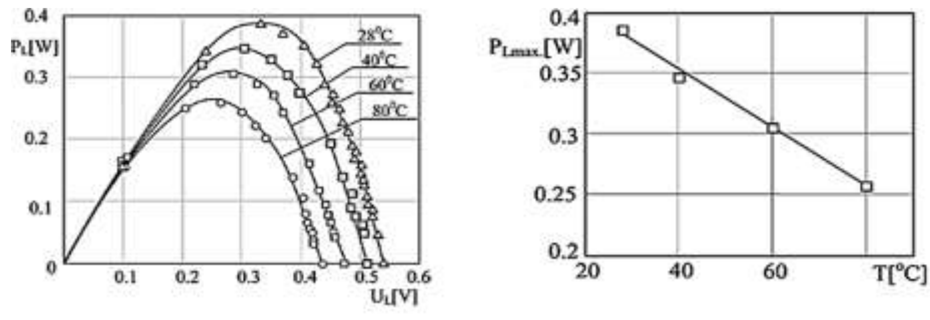

Fig. 3. Linear drop in maximum power output of PV module with temperature increase [12].

Commercially available PV cells are about 14-22% efficient in converting solar energy into electricity depending on the cell technology. Since PV technology is becoming more advanced, higher conversion efficiencies have been achieved. As by June 2016, SunPower holds the record for the world's most efficient rooftop solar module, achieving conversion efficiency of 21.4% [13].

MOST EFFICIENT PV PANEL AVAILABLE COMMERCIALLY [13].

Manufacturer	Model	Type	Efficiency
SunPower	X21-345	Monocrystalline	21.4 %
Sanyo	HIT Double 195	Monocrystalline	20.5%
AUO	Sunforte PM318B00	Monocrystalline	19.5%
Phono Solar	PS330P-24/T	Monocrystalline	17%

Overheating effect on PV Efficiency

One of the main obstacles that face the operation of photovoltaic panels (PV) is overheating due to excessive solar radiation and high ambient temperatures. Overheating reduces the efficiency of the panels dramatically. The ideal P–V characteristics of a solar cell for a temperature variation between 0 ^0C C and 75 ^0C are shown in figure.

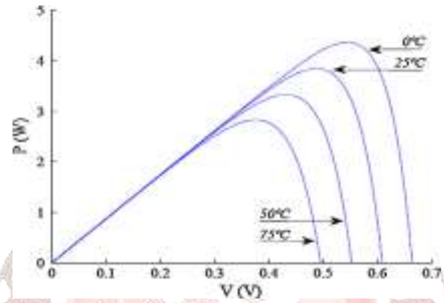

Fig. 4. The influence of PV panel temperature over output parameters [32]

The P–V characteristic is the relation between the electrical power output P of the solar cell and the output voltage V, while the solar irradiance E, and module temperature Tm, are kept constant. If any of those two factors, namely Tm and E, are changed the whole characteristics change. The maximum power output from the solar cells decreases as the cell temperature increases, as can be seen in figure. The temperature coefficient of the PV panels is, 0.5%/ ^0C which indicates that every 1 ^0C of temperature rise corresponds to a drop in the efficiency by 0.5%. This indicates that heating of the PV panels can affect the output of the panels significantly [32].

Dust Accumulation

The second major problem of the commercial PV technology is its cleaning issue, i.e. dust impact and other particles accumulated on the front PV panel surface that can significantly reduce the amount of delivered electricity (in some cases reduction can go up to 30%). The previously mentioned issues (facts) can be overbridged through the improvement of existing market available technologies or through development of novel PV technologies. One possible option is to provide an increase in panel electrical efficiency along with solving its cleaning issue and aiming to develop feasible cooling techniques for the PV panel. It would additionally be useful to investigate the dust effect on panel performance in detail for different levels of dirtiness (tricky issue would be definition of the dirtiness level). Furthermore, it would also be important to provide a clear contribution to the proposed cooling technique in relation to the panel performance [14].

Current Matching Problem

In addition, for a given power output of a PV module where several cells are electrically connected in series, the output voltage increases while the current decreases due to series connection, hence reducing Ohmic Losses. Nonetheless, the cell producing the least output in series string of cells limits the current; this is known as *Current Matching* issue Because the cell efficiency decreases with increasing temperature, the cell having the highest temperature will limit the efficiency of the entire string. Consequently, maintaining a homogeneous low temperature distribution across the string of cells is essential for an optimum performance of PV systems [15].

Non Uniform Illumination

The solar cell under concentration undergoes a series of losses based on the concentrator geometry, optical losses, reflection losses, tracking losses and non-uniform illumination [17]. All these losses occurring in the system tends to increase the temperature of the cell and series resistance which lowers the overall efficiency. In the case of concentrated systems, due to errors induced by geometry, there is an uneven distribution of radiation flux and non-uniform temperature across the surface of PV panel. Non-uniformity has a major impact on the performance of PV system and directly effects cell temperature, series resistance and efficiency.

There is an uneven distribution of radiation flux and non-uniform temperature across the surface of PV panel. Non-uniformity has a major impact on the performance of PV system and directly effects cell temperature, series resistance and efficiency. Non-uniformity results in:

- Increase in cell temperature
- Increase in series resistance
- Decrease in fill factor
- Decrease in conversion efficiency

Due to non-uniform distribution, current mismatch problems and hotspot occurs on the cell resulting in either reduction in efficiency (short term loss) or permanent structural damage due to thermal stress (long term loss). Reduction in efficiency was found to be main effect resulting in increase in overall cost per unit power of PV System. This loss in efficiency due to reduction in fill factor and open circuit voltage. It is observed that as a result of non-uniform illumination 40 % of energy is lost [16].

THERMAL MANAGEMENT OF SOLAR PHOTOVOLTAIC (PV) PANEL

Introduction

Cooling of PV panels is a vital factor in the design and operation of solar cell. The cooling method should be such that it keeps the cell temperature at its minimum with a uniform distribution [17]. Due to the temperature influence on the performance of PV cells, the energy that is unutilised for electrical energy conversion must be extracted to prevent excessive cell heating and deteriorated performance. Therefore, solar cell cooling must be an integral part of PV systems, Various methods can be employed to achieve cooling of PV systems. Challenges are mainly present in hot and humid climate regions where cells may experience both short and long-term degradation due to excessive temperature.

Conventional cooling Methods

Conventional methods of cooling PV panels fall mainly into three categories, namely passive and active cooling.

- Passive cooling
- Active cooling
- Phase Change Materials (PCMs)

Passive Cooling Techniques

Passive cooling techniques refers to ways applied to extract and minimize heat absorption from the PV panel without additional power. consumption. The mechanism implies transporting heat from where it is generated and dissipating it to the environment [18]. Wide varieties of passive cooling options are available, simplest forms involve application of solids of high thermal conductivity metals, such as aluminium and copper, or an array of fins or other extruded surfaces to enhance heat dissipation to the ambient [19]. More complex systems involve the use of Phase Change Materials (PCMs), in addition to the use of Heat Pipes that are able to transfer heat efficiently through a boiling-condensation process However, in such thermal management systems heat dissipation is limited by the contact point between the heat-sink and the ambient, where the convective heat transfer coefficient and to a much less degree the radiative heat transfer are limiting factors. An example illustrating passive cooling of PV panels can be of an array installed on a roof of a house with heat-sinks attached at the rear surface, in a way that allows air to naturally flow behind the panels, and extracts away heat through air convection, or the use of white-coloured roof that prevents the surfaces around the panels from heating up causing additional heat gain. Conversely, with passive cooling the main heat transfer mechanism for a PV system on a windless day is through radiation and free convection, and both mechanisms are of the similar low order of magnitude, therefore, the need for a cooling system that can actively dissipate heat is essential especially in hot climate regions.

Active Cooling Technique

On the other hand, active thermal management techniques comprise of heat extraction utilizing devices such as blowers or fans to force air or pump water to the panels under operation allowing for excessive thermal energy to be extracted. Active cooling means are powered using energy to affect some kind of heat transfer usually by convection and conduction. Although an active system consumes power, they are commonly applied in situations where the added benefit to the panels is greater than the energy demanded to power the system. These systems may also be used in situations where some additional benefit can be achieved, such as waste heat recovery for domestic space and water heating applications.

Fig. 5. Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation [33].

Hybrid solar Photovoltaic/Thermal system represent the following components: (1) PV module (2) Forced circulation fan (3) Air channel.

For both passive and active cooling systems, the commonly used cooling mediums are air and water. However, the thermal properties of air make it less efficient as a coolant medium [20]. Therefore, air cooling is not well suited to the extraction of thermal energy from the PV collectors operating in hot regions. This implies that more parasitic power to operate fans will be needed to achieve the same cooling performance of water, in addition to the limitations affecting thermal-waste recovery when using air as heat extract in medium. Nonetheless, in some situations where water is limited, air may still be the perfect option. Water cooling on the other hand, permits operation at much higher temperature levels and allows waste heat recovery to be employed more efficiently. Hence, air cooling is less favourable option in many cases. Many active cooling systems work in tandem with passive cooling elements to function more effectively. Therefore, the choice of the cooling approach and medium is highly dependent on the PV system design requirements and the conditions at which the system operates.

Waste Heat Recovery

Waste heat refers to energy that is generated in industrial processes without being put to practical use. Energy recovery comprises of practical means of minimizing the input of energy to an overall system by the exchange of energy from one sub-system of the overall system with another [21]. Solar photovoltaic systems in operation experience great deal of thermal energy that is inseparable from the photo-electric conversion process. Thermal energy recovery within PV systems is twofold, serving as cooling mean to the PV module and thus improving its electrical performance as well as collecting the thermal energy by-product, permitting its use in various applications. Hybrid collectors can serve as electrical generators and aid either water or space heating. Alternatively, the thermal energy can be harnessed in a thermo-electric conversion processes when electrical energy is of higher demand.

Thermoelectric Generators (TEGs)

Thermoelectric converters are solid-state semiconductor devices that can convert thermal energy directly into electricity or vice versa. Thermoelectric devices are categorized into two types of converters, depending on the energy conversion process; Thermoelectric Generators (TEGs), and Thermoelectric Coolers (TECs). Thermoelectric generators have immense potential for waste heat recovery from power plants, automobile vehicles, and solar energy applications. The minimal maintenance requirement of TEGs is a distinct advantage as site visits can be reduced to coincide with the annual preventive maintenance cycle of the telecom equipment powering in remote areas. Therefore, TEG device have proven to be the most reliable power source available for the rugged demands of the industry and various scale applications [22]. On the other hand, thermoelectric coolers have been widely used in electronic devices and medical instruments as they can provide refrigeration and temperature control for such devices allowing them to operate at a certain temperature level utilizing the *Peltier Effect*. The use of thermoelectric generators (TEGs) for the thermal management design proposed for PV systems looks promising.

Air based PVT Collectors

Air-based PVT collectors are fabricated by incorporating air channels often present at the rear of a PV laminate allowing naturally or forced ventilated air to flow and extract accumulated heat through convective heat transfer. The use of forced air enhances heat extraction resulting in further improved performance of the PV cells when compared with naturally ventilated ones. Nevertheless, parasitic power losses are introduced due to the use of air blowers, hence affecting the net electrical output [23]. Owing to minimal use of material and low operating costs among other PV cooling technologies, ventilated PVT systems have found broad range of applications in which warm air is required for space heating, agriculture/herb drying, as well as electricity generation [24]. However, due to low density and small heat capacity of air, improvements in the practical performance of air-based PVT collectors are limited, making air thermal management techniques less favourable option in certain situations. Nonetheless, such designs are attractive in situations where water is limited.

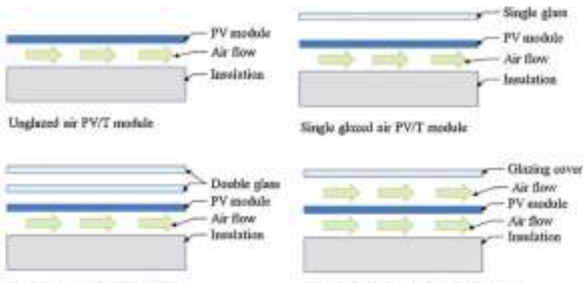

Fig. 6. Different designs of air-based PVT collectors [24].

Liquid based PVT collector

Liquid cooling offers a better alternative to air cooling utilizing coolant as heat extraction medium to maintain desired operating temperature of PV cells and a more efficient utilization of thermal energy captured [25]. Liquid-based PVT collectors are superior to air-based collector’s due to higher specific heat capacity of coolants employed, leading to further improved overall performance. In addition, liquid-based PVT collectors offer less temperature fluctuations compared to air-based PVT making them more favourable [26]. The most common liquid-based PVT collector design comprises of metallic sheet-and-tube absorber in which heat extraction is attained via pumped fluid circulation through Series or parallel connected pipes adhered to the rear of PV collector.

Heat Pipe based PVT Collectors

Heat pipes are considered efficient heat transfer devices that combine the principles of both thermal conductivity and phase transition. A typical heat pipe consists of three sections namely; evaporator, adiabatic, and condenser sections. Heat pipes provide an ideal solution for heat removal and transmission, with one end serving as a thermal energy collector and the other end as a thermal energy dissipater. Heat pipes have been considered for thermal management applications of PV technology due to the advantages such technology provide over other cooling means such as aiding uniform temperature distribution of PV cells [27].

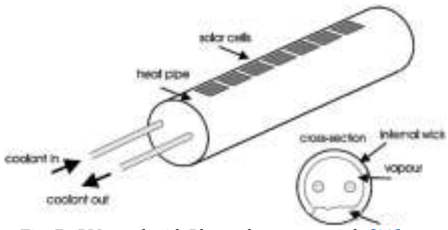

Fig. 7. PV panel with Phase-change materials [22].

Phase Change Material Based PVT Collector.

Phase changes Materials (PCMs) are substances that can absorb and release large amount of energy as latent heat through a reversible isothermal process at a particular phase transition temperature. Latent heat storage using PCMs is superior to sensible heat storage due to their higher energy storage density within a smaller temperature range. As far as PV systems are concerned, conventional passive cooling techniques are unable to provide the required cooling during peak solar radiation periods leading to a deteriorated performance of PVs. Furthermore, non-uniform temperature profiles which affect the generation capacity of PV systems stand as a limitation in other passive cooling methods [28].

One technique that can be used to reduce the surface operating temperature of a PV panel in order to reach a higher electrical efficiency is by incorporating phase-change materials (PCM), such as tungsten photonic crystals. PCM is a latent heat storage material, which is situated on the back part of the PV panel as seen in Fig. 8. When the temperature increases, the chemical bonds within the PCM separate as phase-changing from solid to liquid occurs. The PCM absorbs heat, due to the phase change being a endothermic process. When the heat stored within the storage material reaches the phase-change temperature, the material starts to melt. The temperature then stabilises until the melting process is completed. It is called latent heat storage material, because the heat is stored during the melting process (phase-change process) [34].

Fig. 8. PV panel with Phase-change materials [22].

Thermoelectric Based System

Thermoelectric (TE) modules are solid-state semiconductor devices that are able to convert thermal energy directly into electrical energy or vice versa. A TE module comprise of thermoelectric elements made of two dissimilar semiconductors, p- and n-type junctions connected electrically in series and thermally in parallel. TE modules possess salient features of being compact, lightweight, noiseless in operation, highly reliable, maintenance free and no moving or complex parts, such devices are categorized into two types of converters depending on the energy conversion process; Thermoelectric coolers have been widely used in electronic devices and medical instrument as they are capable of providing refrigeration and temperature control for such devices allowing them to operate at a certain temperature level utilizing the Peltier effect [30]. The most common design of TE cooler for PV (PV-TEC) systems comprise of TEC module installed at the rear PV cell with aluminium sheet in between so as to spread the heat dissipated at the back surface of the PV cell In such system, a fraction of the generated power by the PV cell is fed to the TEC module to provide the necessary cooling effect for the PV cell. The cooling effect of a TEC module is characterized by the amount of power supplied, meaning the more electricity is fed into the TEC module the greater the cooling effect for the PV cell. However, there is a trade-off between the net generated power by the system and the power consumed by the TEC module, in which substantial amount of power is required to achieve significant amount of cooling which can exceed the generated power by PV cells. Therefore, several approaches and control algorithms can be applied by controlling the temperature of the PV cell and keeping it under a specific limit under different conditions or optimization to find the optimal value of the supplied electrical current for the TEC module which leads to the maximum net generated power [31].

The numbers on the figure below represent the following components: (1) Glass cover, (2) PV cells, (3) Insulator, (4) TEG module, (5) Fin heat sink.

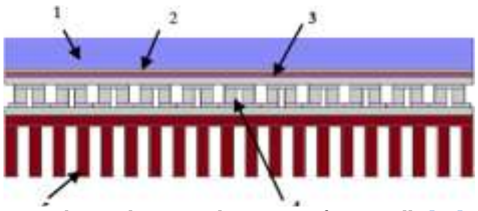

Fig. 9. Thermoelectric cooling system for PV cells [27].

Thermoelectric devices comprise an n-type semiconductor and p type semiconductor, which are connected in series electrically and in parallel thermally. Under a temperature gradient, the majority charge carriers diffuse from the hot side (positively charged electrode) to the cold side (negatively charged electrode) due to the Peltier effect, which creates a voltage that results in current flowing. When a voltage is applied across the material it forces a current to flow through it, which causes the heat pump to cool the one side and heat the other, which must be connected to a heat sink for excess heat dissipation. The thermoelectric cooling system described, can be seen in Fig. 9 [8].

TRANSPARENT COATING (PHOTONIC CRYSTAL COOLING)

A technique that can be used to reduce the surface operating temperature of a PV panel in order to reach a higher electrical efficiency involves incorporating transparent coating (photonic crystal cooling). This visible transparent thermal blackbody is based on silica photonic crystals and is placed on the top surface of the PV cells, and it has the capability to reflect heat generated by the PV cells in the form of infrared light (thermal long infrared transparency window, which is in the 8–30 µm range) under solar irradiance back into space [35]. Simultaneously, the PV cells are slightly enhanced by anti-reflection and light trapping effects. Therefore, the PV cells are cooled by enabling more photons to be absorbed by the PV module. A PV module cooled by transparent coating (photonic crystal cooling) is shown in figure below.

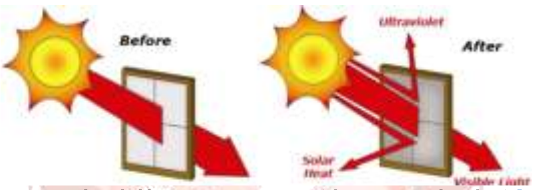

Fig. 10. PV panel cooled by transparent coating (photonic crystal cooling) [35].

DISCUSSION

Various methods can be employed to achieve cooling action for PV systems. However, the optimum cooling solution is critically dependent on several factors such as, system arrangement, PV technology employed, types of concentrators, geometries, and weather condition at which the system is installed.

Hybrid PV System offer a practical solution to increase the electrical power production from PV panels and reduce the heating loads, in addition to the recovery of heat extracted from the panels. Various cooling technique air, liquid, heat pipe, PCM, and thermoelectric modules to aid cooling of PV cells were discussed along with the parameters influencing the system performance.

Air cooling of PV system provides a simple technique to thermally regulate the temperature of PV cells owing to minimal use of material and Low operating cost among other PV cooling technologies. Forced air enhances heat extraction resulting in further improved performance of air PVT systems when compared with naturally ventilated ones at the expense of some parasitic power losses introduced due to the use of air blowers. Nevertheless, the low density and small heat capacity of air, limits the improvements in the performance of air PVT collectors making air less favourable option.

Liquid cooling offers a better alternative to air cooling utilising coolant allowing a more efficient utilization of thermal energy captured. In addition, liquid-based PVT collectors offer less temperature fluctuations compared to air-based PVT making them more favourable in aiding a homogenous temperature distribution on the surface of PV modules. Water is the most common fluid employed in liquid-based cooling of PV systems.

The use of heat pipe cooling of PV cells aids a uniform temperature distribution of PV cells in addition to elimination of freezing that thermosyphon tube used in water-based cooling. PCMs however, offer both high heat transfer rates and heat absorption due to latent heating, which make them attractive for PV cells cooling application.

The incorporation of thermoelectric devices with PV systems seems very attractive when operating at generation mode, however, the supplemental energy generated by the thermoelectric device requires large temperature difference across the hot and cold plates of the device, making improvement in performance limited with the current technologies available.

SCOPE FOR IMPROVEMENT AND VALUE ADDITION

The following are the scope for improvement and value addition to the existing solar photovoltaic system so as make it more efficient by doing the proposed design improvement for the research work.

- Use of thermoelectric devices on the back side of photovoltaic system so as to take heat from the photovoltaic panel and generation of supplementary electricity through thermoelectric generator.
- Use of heat pipe and providing the heat sink arrangement at the end section of heat pipe where the heat will be rejected, that rejected heat may further used in as heated water for household purpose.
- The above proposed system can be tested with the used of SMPS fan over the fins.
- Spray of water at selected interval over the photovoltaic panel during the day time.

- Providing the fins at the back side of photovoltaic panel and transfer of heat either by natural or forced convection.

PROPOSED COOLING TECHNIQUES FOR THERMAL MANAGEMENT

The following techniques are proposed for thermal management of solar photovoltaic panel through literature studied,

- Water cooling at the selected interval during the day time to reduce the temperature using mechanism similar to windshield wiper used in automobile that will simultaneously solve the issue related to heat generation and dust accumulation. Cleaning and temperature control can be done by the proposed technique.
- Use of Peltier device on the back side of solar photovoltaic panel, heat generated is absorbed by PV panel will be absorbed by one end of Peltier device and removed by using water in contact with the other end. Potential difference between two ends will generate supplementary power.
- Use of heat pipe heat exchanger with fins connected to long heat pipes that will be attached on the back side of solar photovoltaic panel. Evaporator section of heat pipe will absorb the heat generated by solar panel and condenser section of heat pipe will remove the heat by transferring it to water.
- Use of heat sinks integrated with solar photovoltaic panel at back side to remove the heat generated either by using natural or forced convection and suitable working fluid air or water.

CONCLUSION

Extensive reviews of various cooling techniques used to enhance the performance of a PV system are discussed in detail in this paper. Proper cooling of PV systems improves the thermal, electrical and overall efficiency, which in turn also reduces the rate of cell degradation and maximizes the life span of the PV module. Several papers from different research fields have been reviewed and discussed based on their focus, contribution and the type of technology used to achieve cooling while trying to increase the efficiency of the panel. As learned from the reviewed studies, the following cooling technologies are found to be promising based on materials used, capital cost and performance:
The conclusions from the reviewed literature are summarised as follows:

- Solar PV systems benefit from the abundant supply of solar energy; hence PV technology has immense potential to tackle ever increasing energy demands.
- Elevated temperature can cause serious degradation to the PV performance, hence cooling of the PV cells must be an integral part of PV systems for efficient operation.
- Cooling of PV cells can be achieved through various techniques; passively, actively, or both working in tandem, with various degrees of cooling capabilities and system complexity.
- Air cooling techniques are considered mature and have been applied in diverse designs, however, improvements in the PV performance are limited due to low density and small heat capacity of air.
- Liquid cooling offers a better alternative to air cooling to accommodate larger margins of temperature rise in addition to efficient caption of thermal energy. However, water in many situations is limited.
- Phase change material have been applied widely to electronic components for thermal management, and ideas have emerged to assess integration with PV technology, however, the utilisation of the thermal energy is complicated, due to the bulkiness of such integration, introducing further complexities and challenges.
- Heat pipes are attractive heat transport mediums functioning as highly concentrating heat exchangers based on the ratio of the evaporator to condenser sections, and thus, heat pipes promote efficient waste heat recovery. Heat pipes are mainly integrated for electronics cooling and realized in many water heating applications.
- Thermoelectric modules have been widely implemented for waste heat recovery applications as power generators, however, they are limited by the operating temperature. Nevertheless, they are solid devices with no moving parts or chemical reactions therefore less maintenance required due to wear and corrosion. In addition, TEGs are also considered one of the few options for direct thermoelectrical conversion.

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