COOLING PHOTOVOLTAIC SYSTEMS: A SURVEY OF AVAILABLE TECHNOLOGIES

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Abstract: Cooling is a key operation factor to take into consideration to achieve higher efficiency when operating solar photovoltaic systems. Proper cooling can improve the electrical efficiency, and the heat removed by the cooling system can be used in other domestic, commercial or industrial applications.
This paper is a survey of various methods that can be used to minimize the negative impacts of the increased temperature while making an attempt to enhance the efficiency of photovoltaic solar panels operating beyond the recommended temperature from the Standard Test Conditions (STC). These technologies are discussed based on their operation principles, technical advantages, and disadvantages. The results of this study highlight that any technology selected to cool a photovoltaic panel should be used to keep the operating surface temperature low and steady, be simple and reliable and, if possible, enable the use of extracted thermal heat to enhance efficiency of the overall conversion system.

Key words: Solar photovoltaic; cooling technologies; conversion efficiency.

1. INTRODUCTION

Globalization and economic growth led to an increase in the consumption of conventional methods of generating electricity mainly using fossil fuels, which have some negative environmental impacts such as greenhouse gas emissions [1-2]. Therefore, there was a need for investigating alternative energy sources such as renewable energy sources, which is a clean and environmental friendly means of producing energy.

A renewable energy technology, such as solar conversion systems can be used for thermal applications like water heating, water purification, cooking, drying, refrigeration and also to generate electricity using the photovoltaic phenomenon. It is pollutant free during operation, diminishes the global warming issue, lower operational costs, minimal maintenance and highest power density among the other renewable energy technologies are the advantages of solar photovoltaic (PV) energy [3-4].

Apart from the several advantages displayed by PV system; this conversion system has some general problems such as hail, dust and surface operating temperature which can negatively affect the efficiency of the conversion system [5]. Where hail could damage the PV module; dust on the surface of the PV module could affect the amount of solar irradiation absorbed by the PV cells and temperature is the most important factor influencing the performance of a PV module. Exogenous climatic parameters such as wind speed, ambient temperature, relative humidity, accumulated dust and solar radiation are the most common natural factors which influence the temperature of the surface of a PV module [6]. Every 1˚C surface temperature rise of the PV panel, cause a reduction in efficiency by 0.5%. If the PV panel surface temperature increases, the PV panel efficiency decreases. Due to the temperature raise, not all of the solar energy absorbed by the photovoltaic cells is converted into electrical energy. To satisfy the law of conservation of energy, the remaining solar energy is converted or wasted into heat. The consequences of this wasted heat cause a reduction in the electrical efficiency and the overall conversion efficiency [7].

Improvements in solar energy conversion systems must be made in order for this renewable energy technology to be a viable solution. To make it a viable solution, there is a need to find different means of solving this temperature problem, which must result in an increase of the overall conversion efficiency.

Very few authors have presented an extensive review of different technologies that can be used to cool the operating surface of solar panels with the aim of increasing the overall efficiency of the solar conversion system.

Sahay et al. have briefly discussed various Solar PV panel cooling technologies. However, only few technologies were introduced while the main focus of the paper was on the testing and performance of a developed Ground-Coupled Central Panel Cooling System (GC-CPCS).

Royne et al. presented an overview of various methods that can be employed for the cooling of photovoltaic cells. While looking closely, it can be seen that the focus of the paper was only on examining the passive, forced air and liquid forced convection cooling methods applied to different solar concentrator systems.

Unlike the above mentioned review studies, this paper provides a comprehensive review on how different technologies can be used to minimize the negative effects of the increased temperature while attempting to improve the performances of PV panel operating beyond the recommended temperature from the Standard Test Conditions (STC). For this purpose, an extensive number of research papers from different authors are used to reach the objectives of the current study.

The following technologies will be discussed and analyzed in this work:

- Floating tracking concentrating cooling system (FTCC)
- Hybrid solar Photovoltaic/Thermal system cooled by water spraying

- Hybrid solar Photovoltaic/Thermoelectric PV/TE system cooled by heat sink
- Hybrid solar Photovoltaic/Thermal (PV/T)
- Improving the performance of solar panels through the use phase-change materials
- Solar panel with water immersion cooling technique
- Solar PV panel cooled by transparent coating (photonic crystal cooling)
- Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation
- Solar panel with thermoelectric cooling

The paper is organized as follows: in Section 2, the basic operation principle of a PV cell is presented. The problem caused by an increase of temperature is clearly explained using equations. In Section 3, the different cooling technologies are described based on their operation principle, advantages and disadvantages. The last section is where a conclusion is made.

2. SOLAR PHOTOVOLTAIC ENERGY TECHNOLOGIES

When a PV cell experiences solar irradiation, the P-N junction absorbs the photon from the incident light, which creates a potential difference across the junction. The charge carriers start to flow and the photocurrent resulted denoted as I_{PV}, which is paralleled by a P-N junction diode.

When investigating the performance of a PV cell, the surface operating temperature plays a crucial part during the PV energy conversion process. Due to high ambient temperatures and high PV panel surface operating temperatures cause overheating of the PV panel, which reduces the efficiency radically [10].

The effect of temperature on the solar panel's electrical efficiency can be analyzed using the following equation:

$$\eta_{PV} = \eta_{T_R}[1 - \beta_R(T_C - T_R) + \gamma \log_{10} I_{PV}] \qquad (1)$$

Where: η_{PV} is the PV module efficiency measured at reference cell temperature, T_R (25°C). β_R is the temperature coefficient for cell efficiency (typically 0.4-0.5/°C) [11]. I_{PV} is the average hourly irradiation incident on the PV module at nominal operating temperature, *NT*. T_C are the PV module temperature and γ is the radiation-intensity coefficient for cell efficiency, which is mostly assumed to be zero [12, 13], reducing the equation to:

$$\eta_{PV} = \eta_{T_R}[1 - \beta_R(T_C - T_R)] \qquad (2)$$

By adding and subtracting the ambient temperature, T_A, to and from the two temperature terms respectively, the following expression is obtained [11]:

$$\eta_{PV} = \eta_{T_R}[1 - 0.9\beta\left(\frac{I_{PV}}{I_{PV,NT}}\right) T_{C,NT} - T_{A,NT} - \beta(T_A - T_C)] \qquad (3)$$

Where: I_{PV} and $I_{PV,NT}$ are the average hourly solar irradiation and the average hourly solar irradiation at NT test conditions. $T_{C,NT}$ (typically 45°C) and $T_{A,NT}$ (typically 20°C) are the cell and ambient temperatures at NT test conditions, respectively. T_A and T_C are the ambient and cell temperature, respectively. When using equation (3), it can be clearly seen that when $T_{A,NT}$ increases, the efficiency decreases.

3. TECHNOLOGIES USED TO INCREASE THE EFFICIENCY OF THE PV BY SOLVING THE TEMPERATURE PROBLEM

In this section the general principle of the operation of the different technologies that can be used to minimize the effect of the increased temperature, while trying to improving the performances of PV panel operating beyond the recommended temperature from the Standard Test Conditions (STC), will be discussed.

A. *Floating tracking concentrating cooling (FTCC)*

A method to achieve optimal output power of a PV module is by using artificial basins for installing PV floating plants. These floating plants consist of a platform with PV modules, set of reflectors and a solar tracking system. Cooling of the PV module is achieved via water sprinklers. Reflectors are used to concentrate the solar radiation to increase the energy harvesting. The floating platform allows for a one-axis tracking system for the positioning of reflectors and also increasing the solar radiation on the PV modules. These plants are called FTCC, the acronym of Floating, Tracking, Concentrating and Cooling [14].

B. *Hybrid solar Photovoltaic/Thermal PV/T system cooled by water spraying*

In this system, the pump draws water from the center of the tank via a suction pipe to avoid dust. The suction pipe consists of a non-return valve and a strainer to avoid sucking of large particles to protect the water pump. After the strainer the water flows through a filter, then sprayed using nozzles over the PV modules. A hybrid Photovoltaic/Thermal (PV/T) system consists of a PV panel and cooling system. The cooling agent, i.e., water, is sprayed on the surface area of the PV panel by using a fan [15]. When spraying water on the surface of the PV module, the temperature decreases and the electrical efficiency increases.

C. *Hybrid solar Photovoltaic/Thermoelectric PV/TE system cooled by heat sink*

Advancements have been made in PV conversion systems, by combining it with a thermoelectric module (TE) and heat sink [16]. The thermoelectric module is placed at the center of the backside of the PV module. One thermo-resistor is placed on top of the TE module and other thermo-resistors in the remaining surrounding areas of the TE module. The temperature increases with time when the PV/TE system is exposed to solar irradiation. There is a small temperature difference between the thermo-resistors, due to the diffusion of charge carriers within the thermoelectric materials when the top and bottom surfaces have a temperature variance. The collected power from the PV module is dissipated into thermoelectric resistors and stored into a battery via an inverter. The heat sink is used for heat dissipation of the PV module, which cools down the surface of the PV module [17].

D. Hybrid solar Photovoltaic/Thermal PV/T

With the aim of increasing the PV system efficiency, a hybrid Photovoltaic/Thermal (PV/T) system generates electrical energy and thermal energy simultaneously [18]. The system consists of a photovoltaic module and thermal solar collector, which is mounted to the backside of the PV module [19]. Collector pipes are used to improve the contact area. Water is used as the circulating fluid, which flows inside the collector via a DC pump, which can be powered by the PV module or other sources. After the heat from the surface area of the PV module is transferred into the circulating water, the heated water flows back to the hot water insulated tank for domestic or other applications.

E. Phase-change materials

A 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 backside of the PV panel. When the temperature increases, the chemical bonds within the PCM separate as phase-changing from solid to liquid occur. The PCM absorbs heat, due to the phase change being a heat-seeking (endothermic) process [20]. When the heat stored within the storage material reaches the phase change temperature, the material starts to melt [21]. The temperature then stays constant until the melting process is finished. It is called latent heat storage material, because the heat is stored during the melting process (phase-change process).

F. Water immersion cooling technique

Another technique that can be used to reduce the temperature of a PV panel is by implementing the water immersion cooling technique. With the water immersion cooling technique a PV module is placed in large water bodies like rivers, oceans, lakes, canals etc. Water is used as the immersing fluid, which absorbs the heat from the PV module and maintains the surface temperature of the PV module. Therefore, when water absorbs the heat from the PV module the electrical efficiency increases [22].

G. 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 is by incorporating transparent coating (photonic crystal cooling). This visible transparent thermal blackbody is based on photonic crystals and is placed on the top surface of the PV cells, which reflects some of the heat generated by the PV cells under solar irradiance back into space [23]. Therefore, the PV cells are cooled by enabling more photons to be absorbed, and thereafter converted into electrical energy.

H. Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation

Another 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 making use of forced air circulation. This system consists of a photovoltaic module, which is placed on top of a steel plate with air channels underneath. Air is used as the working fluid, which is forced through the channels with a fan by means of a nozzle. The heat from the PV panel is transferred to the air in the channels, therefore reducing the surface operating temperature in order to reach a higher electrical efficiency [24].

I. Thermoelectric cooling system

Thermoelectric devices comprise of 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 to the cold side, which creates a voltage that results in current flowing. When a voltage is applied over 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 [8].

4. DISCUSSIONS

After investigating the various technologies used to deal with the temperature problem with the aim of increasing the efficiency, it is imperative to summarize the findings in an easy and accessible way to any party interested in these technologies; this is done in Table 1.

This table provides the advantages, disadvantages, cost, efficiency and the comments to justify the uses of these different technologies.

After analyzing this table, it can be concluded that any cooling arrangement selected should be used to keep the photovoltaic cell temperature low and steady with the aim of increasing the electrical efficiency. It should also, if possible, allow the use of extracted thermal heat to be used for other meaningful purposes.

TABLE I: DISCUSSION ON SOLAR PHOTOVOLTAIC COOLING TECHNOLOGIES

Technology	Advantages	Disadvantages	Cost	Efficiency	Comments
Floating tracking concentrating cooling (FTCC)	Avoid energy dispersion problems by using hydro-electric basins. Avoid electric grid stress by using a pumping scheme to store energy. These systems operate highly efficient [14].	Evaporation of water and therefore water being wasted. The sprinklers cannot spray the entire surface of the PV module and therefore, only parts of it will be cooled [15]. Take long to recover capital cost [14].	High	Increased	The FTCC system operates efficiently, due to combination of the components. Nevertheless, when spraying the water on the surface of the PV module, the whole surface area of the PV panel cannot get sprayed (only parts of it are cooled). Also, water is wasted during evaporation. Due to high manufacturing costs, the return on investment period is 5 years [14].
Hybrid solar Photovoltaic/ Thermal PV/T system cooled by water spraying	Generates more energy with cooling technique than without [15]. More efficient than compared to air cooling.	The whole surface area of the PV panel cannot get sprayed and therefore, only part of the PV panel will be cooled. Heat energy wasted by spraying water [15].	Medium	Increased	With the water spraying system, the experimental results showed that an efficiency increase was obtained. But, water was wasted and the heat energy should be utilized. High manufacturing costs, mainly for the PV panels. Return on investment period is much shorter than FTCC systems [15].
Hybrid solar Photovoltaic/ Thermoelectric PV/TE system cooled by heat sink	The temperature with heat sink decreased by 8.29% [17]. Improves the efficiency of the PV cell. Alleviates hot spotting, which is due to PV cell being unevenly heated during operation.	Heat conduction loss through semiconductors between hot and cold parts Turbulent airflow with the pin fin heat sink [17]. Thermal energy is wasted into the air, rather than utilizing it to improve electrical efficiency.	Medium	Increased	To decrease the surface operating temperature using a heat sink, can be noticed as viable when looking at the experimental results [17]. However, the turbulent airflow makes the heat sink highly unstable. Future research must be carried out on improving the thermal stability of this system. By making use of a thermoelectric module, the return on investment period will decrease drastically.
Hybrid solar Photovoltaic/ Thermal (PV/T)	The energy and emissions payback time are much shorter than the expected lifetime of module, which makes it environmentally viable [18]. An increase in electrical efficiency is found when combined. Utilize heated water for domestic applications.	The optimal efficiency of a PV module cannot be achieved, due to constant flow rate. Need subsidies for these systems.	Medium	Increased	The hybrid PV/T system operates effectively when it comes to increasing the electrical efficiency of the PV module. However, it cannot reach optimal efficiency, due to the flow rate kept constant, rather adjusting the flow rate according to the temperature change to achieve optimal efficiency. Due to the presence of the circulating fluid, the electrical output power increased by 20%. Therefore, the energy payback time decreases.
Hybrid PV/PCM	Store large amounts of heat with small temperature changes [20]. The phase-change at a constant temperature take time to complete, it becomes possible to smooth temperature variations. Absorbed heat can be used to heat buildings.	Paraffin has low thermal conductivity in their solid state. Segregation is formation of other hydrates or dehydrated salts that tend to settle out and reduce the active volume available for heat storage. Less efficient in colder areas.	Medium	Increased	The PCM shows to operate effectively. The system stores the heat from the PV panel during the melting process, however the absorbing capabilities of the PCM material degrades over a long period of time. Also, this system will not achieve the same performance between cold and hot climatic conditions. The energy payback period will be shorter and the lifetime of the PV panel will expand [20].

Technology	Advantages	Disadvantages	Cost	Efficiency	Comments
PV panel with water immersion cooling	Highly efficient Economic Environmentally friendly system [22]. Electrical efficiency increased during clear days when using water immersion cooling technique. Land requirements not needed, by using rivers, oceans, lakes, canals etc.	Lower efficiency during cloudy days. Water is a conductive liquid which when decomposes into its ions may affect the electrical efficiency as the ions will also have a current. The submersion depth influences the efficiency vastly [22]. Electrical efficiency degrades when PV panel is submerged in ionized water for a long time.	Low	Increased	When the water immersion cooling technique is used, the temperature reduced and efficiency increased. The energy payback period is short for this cooling technique. However, there are many factors which need to be taken into account, such as the depth of the PV panel in the water, water cause degradation in the electrical efficiency of the PV panel, etc. It's crucial to use deionized water as the immersing fluid [22].
PV panel cooled by transparent coating (photonic crystal cooling)	Economic and environmental friendly solution. No space requirement needed. Temperature of the PV panel is reduced dramatically [23].	Heat reflected into space is wasted and could rather be utilized. It becomes quite involved when it comes to designing of the photonic crystal and improving it.	Medium	Increased	The PV panel cooled by transparent coating (photonic crystal cooling), the temperature problem is eliminated completely, which enhances the efficiency of the PV panel and reduces the energy payback period. However, heat is wasted and could rather be utilized.
Hybrid solar Photovoltaic/ Thermal system cooled by forced air circulation	The overall efficiency of the system has increased. Economically viable [24]. Heated air can be used in cold climatic conditions for building heating.	The efficiency cooling with air is lower than with water. Not very effective in hot climatic conditions when compared to water cooling.	Medium	Increased	The PV panel cooled by forced air circulation is very effective, but more effective in cold climatic conditions than hot climatic conditions. Also, the electrical efficiency with forced air circulation cannot reach the same optimality than that of forced circulation. Higher efficiency with forced air circulation, which will reduce energy payback time.
Hybrid PV/TC system	It's a clean source of energy. Waste heat is put into useful energy. Increase the life span of a PV module [8].	More efficient in hot regions. Slow technology progression. Requires a relatively constant heat source Low conversion efficiency rate.	Medium	Increased	The hybrid PV/TC system can effectively use the waste heat for higher efficiency, but it has a low conversion efficiency rate and the progression of this technology is slow. The return on investment period reduces drastically when using thermoelectric cooling.

5. Conclusion

Proper cooling is a key operation factor to take into consideration to achieve higher efficiency when operating solar photovoltaic systems. This review has presented an overview of various methods that can be used to minimize the negative impacts of the increased temperature while making an attempt to enhance the performances of PV panel operating beyond the recommended temperature from the Standard Test Conditions (STC). It includes the application to photovoltaic cells of cooling alternatives, namely Floating tracking concentrating cooling system (FTCC), Hybrid solar Photovoltaic/Thermal system cooled by water spraying, Hybrid solar Photovoltaic/ Thermoelectric PV/TE system cooled by heat sink, Hybrid solar Photovoltaic/Thermal (PV/T), Improving the performance of solar panels through the use phase-change materials, Solar panel with water immersion cooling technique, Solar PV panel cooled by transparent coating (photonic crystal cooling), Hybrid solar Photovoltaic/Thermal system cooled by forced air circulation and Solar panel with thermoelectric cooling.

Different tools have been used to illustrate and compare the various technologies used to address the problem of temperature in terms of their advantages, disadvantages and technical implementation.

After analyzing the different technologies, it can be concluded that any cooling arrangement selected should be used to keep the photovoltaic cell temperature low and steady, be simple and reliable, keep parasitic power consumption to a minimum and, if possible, enable the use of extracted thermal heat to enhance efficiency of the overall conversion system.

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