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A review of solar photovoltaic systems cooling technologies

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ABSTRACT

Cooling the operating surface is a key operational factor to take into consideration to achieve higher efficiency when operating solar photovoltaic systems. Proper cooling can improve the electrical efficiency, and decrease the rate of cell degradation with time, resulting in maximisation of the life span of photovoltaic modules. The excessive heat removed by the cooling system can be used in domestic, commercial or industrial applications.

This paper presents a review 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 of the Standard Test Conditions (STC). Different cooling technologies are reviewed, 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) cooled by forced water circulation; Improving the performance of solar panels through the use of 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.

Several research papers are reviewed and classified based on their focus, contribution and the type of technology used to achieve the cooling of photovoltaic panels. The discussion of the results has been done based on the advantages, disadvantages, area of application as well as techno-economic character of each technology reviewed.

The purpose of this review is to provide an understanding for each of the above-mentioned technologies to reduce the surface temperature of the PV module. The study will focus on the surface temperature reduction array bound by each of the cooling technologies. The performance of each cooling technology will also be highlighted. In addition to this study, this review will include a discussion comparing the performance of each cooling technology. The outcomes of this study are detailed in the conclusion section.

This paper has revealed that any adequate technology selected to cool photovoltaic panels should be used to keep the operating surface temperature low and stable, be simple and reliable and, if possible, enable the use of extracted thermal heat to enhance the overall conversion efficiency. The presented detailed review can be used by engineers working on theory, design and/or application of photovoltaic systems.

1. Introduction

One of the most widespread technologies of renewable energy generation is the use of photovoltaic (PV) systems which convert sunlight to into usable electrical energy [1,2]. This type of renewable energy technology which is pollutant free during operation, diminishes global warming issues, lowers operational cost, and offers minimal maintenance and highest power density compared to the other renewable energy technologies, highlights the advantages of solar photovoltaic (PV) energy [3,4]. Apart from the several advantages displayed by the PV technology, this conversion system does have some general problems, such as hail, dust and surface operating temperature which can negatively affect the efficiency of the conversion system [5]. 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 surface temperature of a PV module [6]. Every 1 °C surface temperature rise of the PV module causes a reduction in efficiency of 0.5% [7]. Therefore, due to the temperature rise, 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 into heat. The consequences of this wasted heat bring about a reduction in

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the overall conversion efficiency.

Efficiency 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 tried to put together and conduct 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.

The authors of the paper cited in reference [8] have briefly discussed various solar PV panel cooling technologies. However, only a 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).

In reference [9], the authors presented an overview of various methods that can be employed for cooling photovoltaic cells. However, when 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 of how different technologies can be used to minimize the negative effects of increased temperature, while trying to improve the performance of a PV panel operating beyond the recommended temperature of the Standard Test Conditions (STC). For this purpose, an extensive number of research papers from different authors are used to achieve the objectives of the current study. Different tools (schematic diagrams, pictures, tables and figures) are used to enhance the content and to offer an effective and simple presentation.

The following technologies will be discussed and analysed 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) cooled by forced water circulation
- Improving the performance of solar panels through the use of 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 operational principle of a PV cell is presented. The problem caused by an increase of temperature is clearly explained using graphs and equations. In Section 3, the different cooling technologies are described based on their operational principle using a suitable visual representation. In Section 4, an extensive tabular list of reviewed works is provided. Information such as the authors, research focus, review contribution and the technology used to address the temperature problem, can be obtained from this table. A discussion of this paper's main findings on the different technologies reviewed are available in Section 5, and the last section is the conclusion.

2. Description of a solar photovoltaic system operation

When a PV cell is exposed to solar radiation, the photon is absorbed by the P-N junction, which creates a potential difference across the junction. The charge-carriers start to flow and the resulting photocurrent is denoted as I_{PV}, which is paralleled by a P-N junction diode.

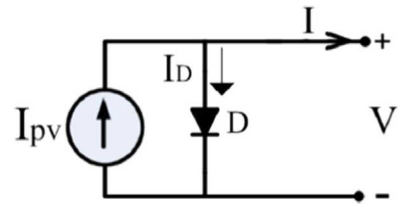

Fig. 1. Equivalent circuit of a PV cell [10].

Investigating the performance of a PV cell shows that the surface operating temperature plays a crucial part during the PV energy conversion process. High ambient temperatures and high PV panel surface operating temperatures cause overheating of the PV panel, which reduces the efficiency radically [11].

Fig. 1 shows that the preferred operating temperature ranges between 0 °C and 75 °C. The P-V characteristics are the relation between the output power and the output voltage, while the solar irradiance, E, and module temperature, Tm, are kept constant.

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

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

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 0.004–0.005/°C) [13]; I_{PV} is the average hourly irradiation incident on the PV module at nominal operating temperature; NT. T_C is the PV module temperature, and Υ is the radiation-intensity coefficient for cell efficiency, which is mostly assumed to be zero [14,15], reducing the equation to:

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

By adding and subtracting the ambient temperature, T_A, to and from the two temperature terms respectively, the following expression is obtained [13]:

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

where: $T_{C,NT}$ (typically 45 °C) and $T_{A,NT}$ (typically 20 °C) are the cell and ambient temperatures, respectively. When using Eq. (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 operational principle of the different technologies that can be used to minimize the effect of the increased temperature, while attempting to improve the performance of a PV panel operating beyond the recommended temperature of the Standard Test Conditions (STC), will be explained technically in order to understand the relevant researches from different authors gathered, reviewed and summarized in Section 4 as well as the discussion in Section 5.

3.1. Floating tracking concentrating cooling (FTCC)

One method to achieve optimal output power of a PV module, makes use artificial basins for installing PV floating plants. These floating plants consist of a platform with PV modules, a 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 for increasing the solar radiation on the PV modules. These plants are called FTCC, the acronym of Floating, Tracking, Concentrating and Cooling. Fig. 2 shows an FTCC system with its main components, where the following numbering represents: