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Experimental analysis and performance evaluation of a tandem photovoltaic–thermoelectric hybrid system

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ABSTRACT

Although photovoltaics have been established as the dominant technology considering the field of solar energy conversion systems, issues regarding their relatively low efficiency still remain practically unsolved. Very recently, the possibility of combining photovoltaic (PV) cells and thermoelectric generators (TEGs) in hybrid systems, as a means of improving the overall conversion efficiency, has attracted particular attention. In this paper, the performance of a tandem PV–TEG hybrid, employing poly-Si as well as dye-sensitized solar cells, has been examined experimentally. Thermoelectric devices of different thermoelement geometry have been tested in order to identify the corresponding performance effect. In addition, the outcomes of the experimental process have been exploited in order to evaluate the performance of the system under real operating conditions. The analysis conducted indicates that the utilization of TEGs with shorter thermoelements results in enhanced power output levels, when conditions of actual operation are considered. Moreover, although improved power output is obtained by the setup employing the polycrystalline cell, dye-sensitized technology could become particularly attractive when the incorporation of solar cells in PV–TEG hybrids operating under conditions of elevated temperature is examined.

1. Introduction

Nowadays, the rapid incorporation of renewable energy technologies within the global energy supply infrastructure has been deemed a necessity, due to the increasing concerns regarding the issues of global warming and climate change. Within this framework, solar energy harvesting has emerged as a promising solution towards the adoption of a clean and sustainable model for electricity production. Photovoltaic technology, directly transforming solar energy into electricity, is currently considered as the most reliable amongst other solar energy conversion alternatives, due to the absence of moving parts, low maintenance requirements and silent operation [1]. Nevertheless, despite the tremendous progress that photovoltaics have achieved so far, their limited efficiency, caused by the inability to fully exploit the wide solar spectrum, raises questions about their competitiveness when compared to fossil fuel based systems [2,3]. Conventional materials can convert effectively only photons of energy close to the semiconductor band gap, which leads to considerable power losses during the conversion process. Currently available single junction Si technologies are limited to maximum efficiencies in the order of 30% [3–5]. As a result, most of the absorbed energy is converted into heat, increasing the temperature of PV cells and leading to further efficiency reduction due to the negative performance temperature coefficients commonly exhibited [6–8].

One way to overcome efficiency issues is to utilize alternative PV technologies, which can effectively exploit larger part of the solar spectrum. In this respect, the combination of different materials with different band gaps (multijunction PV cells) in one cascaded device for capturing a larger fraction of the solar spectrum has been proposed [9,10]. Moreover, the use of specialized materials with intermediate energy levels within the semiconductor gap has also attracted attention [11]. In both cases, the expected efficiencies are far beyond those achieved by conventional photovoltaic materials. However, these technologies tend to be quite expensive and their commercialization status still remains unknown.

A different approach in order to increase the intensity of incident irradiation and harvest more power per unit area of PV material is the employment of mirrors or lenses for solar concentration purposes [12]. Nevertheless, this method leads also to significant increase of cell temperature, causing further efficiency reduction and in extreme cases cell degradation [13]. For these reasons, some means of cooling the PV device has to be utilized in order

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to effectively overcome the temperature increase. In the past several passive as well as active cooling methods have been examined [14]. Hybrid photovoltaic/thermal (PV/T) systems, that couple PV devices to heat extractors using air or water for cooling the cells, are considered the most attractive solution, attaining higher efficiency levels due to the additional thermal energy harvesting achieved [15–17]. Cooling of the PV cell enhances its own efficiency while a portion of the unexploited part of the solar spectrum can be harvested back in the form of hot water or air, leading to further improvement of the overall performance.

Very recently, the combination of thermoelectric and photovoltaic technology in a hybrid system has also attracted increasing attention as an alternative method for cooling of the PV cells and enhancing conversion efficiency. TEGs are solid state devices of heat engine type that can take advantage of existing temperature gradients for electricity production. Despite the absence of moving parts and reliable operation, their use is restricted to specialized situations due to their relatively low efficiency [18,19]. Nevertheless, the utilization of TEGs for power generation purposes can become particularly attractive when considering waste-heat recovery applications, which is also the case for PV systems where the major part of the solar spectrum absorbed is converted into heat.

Early estimations regarding the feasibility of poly-Si based PV–TEG hybrids indicated efficiency enhancement up to 23%, however reflection and heat losses have been neglected during calculation [20]. More recently, theoretical models have been developed in order to identify the most appropriate photovoltaic technologies for integration in PV–TEG hybrid systems. The results suggest that poly-Si thin film cells would be more suitable for concentrating PV–TEG hybrids, while polymer solar cells would better fit non-concentrating configurations [21]. The outcomes of similar analytical models underlined that only in the case of a-Si technology the performance of the hybrid system would be improved compared to the PV cell alone, however the comparison has been conducted with respect to cell operation at 25 °C, which is not always a realistic scenario, especially for hot climates [22]. Theoretical investigation examining the incorporation of nanofluid as the heat extraction mechanism revealed better performance, in relation to similar hybrid systems operating with water [23]. In addition, performance analysis of a PV–TEG hybrid system, based on a thermodynamic method, provided overall efficiency enhancement in the order of 27%, compared to a single mono-Si PV module operating at 345 K [24]. Numerical investigation of a heat pipe-based hybrid generator indicated considerable efficiency improvement for the hybrid system with respect to a stand alone silicon PV panel operating at the same environment, especially for low wind speed and high ambient temperature conditions [25]. Moreover, analytical studies examining the performance of a poly-Si based PV–TEG configuration in various locations around Europe throughout the year, resulted in maximum gain of approximately 14% for the total annual energy produced due to TEG integration, while the thermoelectric contribution recorded was more substantial for towns located in Southern Europe [26]. A theoretical model aiming to evaluate the performance of a concentrating PV–TEG system, incorporating different PV cell technologies as well as phase change materials for limiting operating temperature fluctuations, led to higher conversion efficiency for the proposed system compared to sole PV and conventional PV–TEG hybrids, with the maximum benefit occurring during midday hours [27]. Theoretical optimization analyses of a hybrid system employing a dye-sensitized solar cell for the photovoltaic part indicated that the overall efficiency improvement is maximized at operating temperature of approximately 340 K, however, the proposed decrease pattern considering cell's power output variation with respect to its operating temperature is linear, which is in contrast to our experimental results, for the dye-sensitized solar cell used here [28]. In addition, experimental testing of a tandem PV–TEG hybrid incorporating a dye-sensitized solar cell resulted in power output improvement of 11.2% compared to stand alone cell performance, although the temperature gradient examined for the thermoelectric part of the system remained below 20 °C, leading to low thermoelectric power output levels [29]. Experimental investigation of a 2-wire hybrid configuration (where the PV and TEG modules are electrically connected in series) employing conventional crystalline Si solar cells, underlined the importance of accurate internal resistance matching between the PV and TEG devices, leading to power output increase ranging from 30% to 250%, which is dependent on the TEG device employed and the temperature gradient established across the thermoelectric part of the system [30]. The incorporation of spectrum splitting mechanisms in PV–TEG hybrids for optimizing solar spectrum distribution and improving the overall system performance has also been examined in the past, however these configurations tend to become complicated, especially for larger scale systems [31,32]. In addition, a novel ultra-broadband photon management structure has recently been proposed as an alternative method for enhancing the performance of PV–TEG configurations [33].

Nevertheless, despite the continuously increasing interest, the majority of the aforementioned studies have solely been focused on the theoretical investigation of PV–TEG hybrid systems. As a result, inadequate information is available regarding the experimental performance validation of PV–TEG configurations. Moreover, little effort has been put on the correlation between experimental data and performance evaluation of such systems under conditions of actual operation. In addition, the integration of alternative photovoltaic technologies (e.g. dye-sensitized solar cells) in PV–TEG hybrids has been rarely considered. Furthermore, critical performance parameters, such as the effects induced when thermoelectric devices of different thermoelement geometry are employed, have not yet been examined.

In this work, the performance of a 4-wire tandem PV–TEG hybrid system, utilizing poly-Si as well as dye-sensitized solar cells, has been evaluated experimentally under laboratory environment. Thermoelectric generators consisting of thermoelements of different length have been tested in order to identify the corresponding performance deviation. Furthermore, a wide range considering the operating temperature of the PV cells has been examined, varying between 25 °C and 86 °C. The resulting minimum and maximum temperature gradient established across the thermoelectric part of the system was 8 °C and 43 °C respectively. Subsequently, the outcomes of the experimental process were exploited in order to estimate the performance of the system under real operating conditions.

According to the theoretical investigation, the corresponding performance enhancement achieved reaches 22.5% for the poly-Si and 30.2% for the dye-sensitized based hybrids respectively, for the maximum operating temperature examined here. In addition, the correlation between experimental and theoretical data revealed that, although thermoelectric power output is considerably improved for devices consisting of longer thermoelements, lower operating temperature of the PV part is ensured when TEGs of shorter thermoelements are used, leading to better overall performance of the hybrid system under conditions of actual operation. This observation can strongly affect the manufacturing costs of PV–TEG hybrid systems, since improved performance is possible despite the utilization of smaller amounts of semiconducting active material. Moreover, although the power output provided by the hybrid setup employing the poly-Si cell remains higher throughout the temperature range examined here, the utilization of dye-sensitized solar cells could become more favorable in financial terms, especially when operation under conditions of elevated temperature is considered.