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Coupled thermal model of photovoltaic-thermoelectric hybrid panel for sample cities in Europe

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ABSTRACT

In general, modeling of photovoltaic-thermoelectric (PV/TEG) hybrid panels have been mostly simplified and disconnected from the actual ambient conditions and thermal losses from the panel. In this study, a thermally coupled model of PV/TEG panel is established to precisely predict performance of the hybrid system under different weather conditions. The model takes into account solar irradiation, wind speed and ambient temperature as well as convective and radiated heat losses from the front and rear surfaces of the panel. The model is developed for three sample cities in Europe with different weather conditions. The results show that radiated heat loss from the front surface and the convective heat loss due to the wind speed are the most critical parameters on performance of the hybrid panel performance. The results also indicate that, with existing thermoelectric materials, the power generation by the TEG is insignificant compared to electrical output by the PV panel, and the TEG plays only a small role on power generation in the hybrid PV/TEG panel. However, contribution of the TEG in the power generation can be improved via higher ZT thermoelectric materials and geometry optimization of the TEG.

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1. Introduction

During operation of the photovoltaic (PV) panel, a portion of the solar irradiation converts to thermal energy and increases the temperature of the PV cell, causing the efficiency to decrease. The cell's operating temperature has a significant effect on its electrical conversion efficiency; so that the power output of the module varies inverse proportional with the operating temperature of the cell [1]. However, this temperature difference with ambient can be suitable to apply TEG and make a hybrid power generation system.

Integration of PV with TEG makes opportunity to broaden harvesting of the solar spectrum. One of key design parameter to improve total power output in hybrid PV/TEG module is to provide higher temperature difference across the TEG module [2].

Solar cells and thermoelectric generators (TEGs) share the attractive technology features of reliability, silent operation, and absence of moving parts. Furthermore, integration of the TEG with the PV cell may enhance overall conversion efficiency of the cell by converting a fraction of the heat generated into electricity by the TEG. During the last decade, several studies have investigated the viability of combining PV with TEG as an integrated module to utilize wasted thermal energy produced by the PV cell [3–7]. However, Makki et al. [8] concluded that the added electricity generation by the TEG is limited by the current technology available in thermoelectricity. Performance investigation of TEG for optical solar concentration [9] shows that solar TEG systems could be efficiently integrated with domestic power generation installations.

In order to improve the overall conversion efficiency of the hybrid module, a number of rational techniques such as spectrum splitting of the solar irradiation [10,11], concentrated PV/TEG [12,13] and applying heat sink underneath of the hybrid module in order to improve the heat conduction [14] have been suggested. Dallan [15] discovered that contribution of TEG with the PV/TEG hybrid system as a heat pump enhances power output of the PV cell in the hybrid module under fixed thermal input conditions in comparison with the power output of the PV cell in absence of the TEG. Fisac et al. [16] indicated that the temperature gradient in the solar cell supplying the TEG has positive contribution to the total electricity generation of the integrated system. Lin et al. [17] determined optimum operating regions of hybrid PV and TEG module based on operating conditions of PV and structural parameters of TEG.

Hashim et al. [18] presented a hybrid PV/TEG model that considers effect of TEG geometry on power generation in the hybrid

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Nomenclature

A	area, m^2
a, b, n	empirical constants
f	thermoelectric fill factor
G	solar radiation, W/m^2
Gr	Grashof number
H	layers thickness in panels, m
h	heat transfer coefficient, W/m$^2 \cdot$K
k	thermal conductivity, W/m$\cdot$K
L	panel length, m
Nu	Nusselt number
P	power, W
Pr	Prandtl number
Q	heat loss/heat transfer, W
Ra	Rayleigh number
T	temperature, K
ΔT	temperature difference, K
V	wind speed, m/s

Greek symbols

α	Seebeck coefficient, V/K
β	PV cell temperature coefficient, 1/K
γ	PV solar irradiance coefficient
ε	emissivity
η	conversion efficiency
θ	angle of inclination from the vertical, °
ρ	electrical resistivity, $\Omega \cdot$m
σ	Stefan-Boltzmann constant, W/m$^2 \cdot$K^4

Subscripts

a	air, ambient
b	bottom
c	cold junction
cr	ceramic, critical
conv	convection
EVA	ethylene vinyl acetate
F	forced
f	front
g	glass
h	hot junction
Si	silicon
N	natural
p	panel
PV	photovoltaic cell
r	rear surface
rad	radiation
ref	reference
sky	sky
t	top
ted	tedlar
TEG	thermoelectric generator
w	wind

module. Their results indicate the overall conversion efficiency and power output can be achieved through geometry optimization of the TEG. Results of a theoretical and experimental study [19] shows a TEG with shorter thermoelements is able to provide lower operating temperature for PV module that enhance overall performance of the hybrid module. This optimization is strongly linked to financial feasibility of the hybrid module.

To model the conventional PV/TEG hybrid modules, most of the suggested analytical models to consider feasibility of the hybrid modules are presented with some ideal assumptions. For example, Van Sark [20] ignored heat transfer through the front cover of the hybrid module including radiated heat loss. Moreover, the PV and TEG models are not thermally coupled in that work, and conversion efficiency of TEG is added to efficiency of PV. Bjørk and Nielsen [21] achieved more realistic results by coupling of PV and TEG models for different types of PV cells indicating that, depending on the PV cell material, the hybrid module can generate a lower or higher power than the PV alone module. In this work, the effect of ambient condition and thermal losses were not included in their calculations.

Integration of TEG with PV cell increases equivalent thermal resistance of the module and decreases the efficiency of the PV cell. On the other hand, as the temperature increases, the thermoelectric efficiency increases. According to results from a coupled PV/TEG model [21], the conversion efficiency of the hybrid system is generally lower than that of the PV alone unless fabrication of low thermal conductive thermoelectric materials with high Seebeck coefficient is possible. Su et al. [22] established an electrical and thermal model of a hybrid dye-sensitized solar cell with TEG to evaluate maximum working states of the device. They showed that there is an optimal operating temperature where the hybrid device has maximum efficiency.

Since heat loss rate is higher in PV panels with lower conversion efficiency, applying TEG on this kind of solar cells is more effectual to enhance the total efficiency of the module. A hybrid thermal and electric model of a dye-sensitized photovoltaic-thermoelectric module is established by Su et al. [23] to show the effects of operating temperature caused by the TEG on performance of the photovoltaic cell. Deng et al. [24] indicated that the efficiency of a low efficiency thin-film cell is doubled due to integration with TEG and an efficient heat collector. Using a micro-scale photovoltaic—thermoelectric hybrid device, Wang et al. [25] elevated the overall conversion efficiency by 13% compared to that of PV cell alone. Furthermore, Mizoshiri et al. [26] increased the open circuit voltage of the hybrid module by 1.3% compared to that of the PV module only by applying thin-film TEG.

As mentioned, the major weakness in most models of hybrid PV/TEG thermal systems is that they are not comprehensive and do not take into account critical parameters such as wind speed, ambient temperature etc. For instance, most of geographical studies of the PV potential consider only the effect of solar irradiation and ambient temperature on the panel electrical conversion efficiency. For example, a hybrid model has been proposed to evaluate performance of PV/TEG system in some cities in Europe [27]. The results indicate that the TEG performs better in the spring and summer seasons and the best performance is obtained for the cities with high solar radiation and low ambient temperature.

This study is based on developing a thermal equivalent network model for PV/TEG hybrid panel that takes into account the natural convection, forced convection and radiation from both of the front and rear surfaces of the panel in evaluation of the panel performance. Real weather conditions of three sample cities in Europe (Aalborg, Denmark, Paris, France and Malaga, Spain) are used in the model to evaluate potential of this technology for various locations. The presented thermally coupled model includes the thermal resistance effect of adding the TEG on the PV performance to compare variation of the conversion efficiency in the PV/TEG panel and in the PV panel.

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