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Modeling and performance analysis of a concentrated photovoltaic–thermoelectric hybrid power generation system

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ABSTRACT

In this study, a thermodynamic model for analysing the performance of a concentrated photovoltaic–thermoelectric generator (CPV–TEG) hybrid system including Thomson effect in conjunction with Seebeck, Joule and Fourier heat conduction effects has been developed and simulated in MATALB environment. The expressions for calculating the temperature of photovoltaic (PV) module, hot and cold sides of thermoelectric (TE) module are derived analytically as well. The effect of concentration ratio, number of thermocouples in TE module, solar irradiance, PV module current and TE module current on power output and efficiency of the PV, TEG and hybrid PV–TEG system have been studied. The optimum concentration ratio corresponding to maximum power output of the hybrid system has been found out. It has been observed that by considering Thomson effect in TEG module, the power output of the PV, TE and hybrid PV–TEG systems decreases and at $C = 1$ and 5, it reduces the power output of hybrid system by 0.7% and 4.78% respectively. The results of this study may provide basis for performance optimization of a practical irreversible CPV–TEG hybrid system.

1. Introduction

The conventional fossil fuels are the most economic power generation sources. Due to escalating energy demand and oil prices, growing concerns about various emissions from fossil fuel combustion are compelling researchers to pay more attention towards renewable energy sources which are economical and viable. Solar energy is the most abundant and clean source among the renewable energy sources. Photovoltaic (PV) cells are used to convert solar energy into electricity. However, the efficient conversion of solar energy into electricity has become the primary aim for researchers. PV cells convert a part of incident absorbed solar radiation into electricity and a significant part is converted into heat. Thus, the thermalization and absorption losses which are more than 50% of incident solar radiation in PV cells limit the application of PV cells. Therefore, the electrical conversion efficiency is only 10–15% due to heat dissipation which causes the increase in PV cell temperature and it is known that a negative correlation exists between PV cell temperature and efficiency. Furthermore, to get higher power output and efficiency per unit area of PV cell, the optical concentrators are used to concentrate solar radiation on PV cells which increases the intensity of incident beam radiation. However, with increase in power output per unit area, the PV cell temperature will also increase significantly in concentrated PV system which results in decrease in PV cell efficiency. Therefore, to overcome this drawback of concentrated PV systems, some means for cooling of PV system should be employed. Several active and passive cooling methods have been proposed since last few decades. Royne [1] presented a comprehensive review on various cooling methods. However, in most of these cooling methods, the dissipated heat in PV systems is rejected to the outside ambient. The most commonly used method for active cooling is photovoltaic–thermal (PV/T) which provide both electricity and heat simultaneously. The innovative idea of conversion of thermal energy into electricity directly using thermoelectric generator (TEG) has been proposed several years back [2]. Van Sark [3] proposed the idea of PV–TEG hybrid system in which, the wasted thermal energy of concentrated photovoltaic (CPV) system can be utilized in TEG by connecting the TEG to the back side of PV module. Since efficiency of photovoltaic (PV) modules degrades at elevated temperatures up to about 25% depending on the module integration type in the roof. The conversion efficiency for roof integrated PV–TE ideal system increases up to 23% for thermoelectric materials having figure of merit of 0.004 K^{-1} at 300 K. However, the model was developed for ideal PV–TE system. Therefore, for practical PV–TE hybrids, the efficiency reduces by 10%. Chavez-Urbiola et al. [4] examined the solar hybrid system

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Nomenclature

A	area (m^2)
C	concentration ratio
E_g	band-gap energy of semiconductor (eV)
G	solar irradiation (W/m^2)
h_0	convective and radiative heat transfer coefficient (W/m^2 K)
I	electric current (A)
k	thermal conductivity (W/m K)
k_B	Boltzmann constant (1.38×10^{-23} J/K)
K	thermal conductance (W/K)
K_I	current temperature coefficient (mA/K)
K_V	voltage temperature coefficient (V/K)
l	length of thermocouple element
L	thickness (m)
n	number of p–n thermocouple elements
n_{id}	diode ideality factor
n_s	number of PV cells in series
n_p	number of strings in parallel
P	electrical power (W)
q	electric charge (1.6×10^{-19} C)
Q	heat (W)
R	electrical resistance (Ω)
R_{L1}	output load of PV module
R_{L2}	output load of TEG module
s	seebeck coefficient (V/K)
T	temperature (K)
U_L	overall heat transfer coefficient (W/m^2 K)
v	wind velocity (m/s)
V	voltage (V)
Z	figure of merit (1/K)

Greek letters

α	absorptivity
β_c	packing factor of PV module
β_0	PV cell temperature coefficient (K^{-1})
μ	Thomson coefficient (V/K)
σ	electrical conductivity (S/m)
ρ	electrical resistivity (Ω m)
τ	transmissivity
η	efficiency

Subscripts

a	ambient
b,ch	bottom, cell to hot side of TEG
c	photovoltaic cell
contact	contacts
conducting metal	conducting metal
eff	effective
g	glass cover
h	hot side of TEG
l	cold side of TEG
max	maximum
n	*n*-type semiconductor material
OC	open circuit
p	*p*-type semiconductor material
PV	photovoltaic module
ph	photo generated
TE	thermoelectric module
ref	reference conditions
rs	reverse saturation
SC	short circuit
Sh	shunt
S	series
T	tedlar
t,ca	top, cell to ambient

with TEG for four different configurations. The experiment study was carried out for Bi_2Te_3 based TEGs with temperature difference of 50–200 °C and it was found that the TEG's efficiency, current and voltage have linear dependency on the temperature difference between hot and cold junctions of TEG. Wang et al. [5] developed a novel PV–TEG hybrid system by inserting a selective absorber between PV and TEG. It was reported that the overall efficiency of combined dye-sensitized solar cell (DSSC) PV–TEG rises up to 13% due to use of solar selective absorber (SSA) and TE with 6.2 °C temperature gradient along the hot and cold junctions which utilizes the low energy solar radiation transmitted through the DSSC. Although the hybrid device was not yet optimized however, it can be used as proof-of-principle convert solar light and heat simultaneously into electricity by a single device with high conversion efficiency. Vorobiev et al. [6] designed a hybrid solar system consisting of a concentrator, PC cell, heat engine and TEG. They discussed two options; in which one having a special PV cell construction, uses the heat energy of solar spectrum which was not absorbed in the semiconductor material of the cell and the other is operating at high temperature which uses concentrated PV cell coupled to the high temperature stage. The analysis has been carried out for different band-gap semiconductor materials and different thermoelectric materials. Zhang and Chau [7–8] proposed and implemented a PV–TEG hybrid system for automobiles in which TEG was employed to utilize the waste heat of exhaust of internal combustion (IC) engine and optimized the power output with maximum power point tracking (MPPT) technique. A prototype is developed and tested to validate the proposed system. He et al. [9] carried out the energy and exergy analysis of a TE cooling and heating system driven by heat pipe PV/T in summer and winter operating conditions theoretically and experimentally. The results show that the electrical and thermal efficiencies of the PV/T panel are 16.7% and 23.5% respectively. The concluded that the energetic efficiency of the system is higher in summer operation mode as compared to that of in winter operation mode. However, the exergetic efficiency of the system is lower in summer operation mode as compared to that of in winter operation mode. Kraemer et al. [10] and Xing Ju et al. [11] developed and analyzed a spectrum splitting PV–TEG hybrid system numerically. They showed that these hybrid PV–TEG systems can maximize conversion efficiency and are more appropriate at higher concentration. Tritt et al. [12] proposed that for TE power generation, the solar radiation can be utilized as heat source. Yang and Yin [13] analyzed the novel PV–TE hybrid system theoretically and experimentally with water pipelines being used as heat sink. The conversion efficiency depends on water flow temperature, solar irradiation and ambient temperature for given material properties of each layer. It was reported that the power output of photovoltaic/thermoelectric/hot water (PV/TE/HW) system is up to 30% higher than PV/HW and conventional PV systems. Guo et al. [14] developed a two-compartment hybrid tandem cell containing a dye-sensitized solar cell (DSSC) at the top and a TE system at the bottom which uses the full solar spectrum in order to increase the overall efficiency of the tandem cell. The efficiency of hybrid tandem cell has been increased by 10% as compared to individual DSSC. Zhang et al. [15] evaluated the efficiency of concentrated PV–TE hybrid system for different PV cells such as copper