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Maximum efficiency and parametric optimum selection of a concentrated solar spectrum splitting photovoltaic cell-thermoelectric generator system

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ABSTRACT

An updated model of the solar spectrum splitting photovoltaic cell-thermoelectric generator system is used to derive the analytical expression of the systemic efficiency. The cutoff energy of the system, cell voltage, and dimensionless current of the thermoelectric generator are optimized. Particularly, the influences of the area ratio of the collector to photovoltaic cell on the performance of the spectrum splitting system are discussed in detail. The maximum efficiencies of the spectrum splitting system are calculated for given solar concentration factors. The results obtained are compared with those of the single photovoltaic cell with the same solar concentration factor. It is found that the maximum efficiency of the system can be further improved when the area ratio is optimized. The expressions of the upper and lower bounds of the optimized area ratio are derived. The spectrum splitting system can more efficiently harvest the full solar spectrum than the single photovoltaic cell, especially at low solar concentration factors. For example, when solar concentration factors are, respectively, equal to 30 and 100, the maximum efficiencies of the spectrum splitting system attain 39.5% and 40.2% and increase approximately 2.67% and 2.19%, compared to those of the single photovoltaic cell.

1. Introduction

Solar energy is the prime renewable energy source because it's clean, renewable, and nearly inexhaustible [1]. The photovoltaic (PV) cell is a widely used device for the direct conversion of solar energy into electricity, but most of solar energy is lost and converted into heat that remarkably reduces the performance of the PV cell [2]. The energy losses in a single junction solar cell mainly include the thermalization, transparency, and recombination losses [3], which restrict the theoretical efficiency limit (~31%) of a single-junction solar cell [4]. Therefore, removing heat from the PV cell is beneficial to reduce the energy losses and improve the conversion efficiency [5]. The thermoelectric generator (TEG) that directly transforms heat into electricity based on the Seebeck and Peltier effects has potential to utilize the solar spectrum that is not absorbed by the PV cell [6]. The coupling system composed of the PV cell and TEG may be an efficient method to enhance the utilization efficiency of solar energy.

There are two design schemes for PV-TEG coupling systems [7]. That the TEG is directly attached on the backside of the PV cell is a common form of the PV-TEG systems. Many experiment and numerical studies have been carried on this form due to its simple structure. For example, Liao et al. [8] discussed the effects of the thermal conductance between the concentrated photovoltaic (CPV) and the TEG, current of the CPV, solar concentration factor, and figure of merit of the TEG on the power output of a low concentrated PV-TEG system and determined the optimal coupling of the load resistances of the CPV and TEG. Lamba el al. [9] analyzed the thermodynamic model of a concentrated PV-TEG system and the influences of the Thomson effect, thermocouple number, PV and TEG currents, and irradiance on the power output and efficiency of the PV-TEG system. Soltani et al. [2] experimentally designed a nanofluid-based cooling method for a PV-TEG system, compared with the conventional cooling method. Cui et al. [10] constructed an experimental PV cell-phase change material (PCM)-TEG system, compared to the pure PV system, and the cost and the effects of the optical concentrations ratio and cooling approaches on the efficiency of the PV-PCM-TEG system were studied. Kil et al. [11] fabricated a concentrating-photovoltaic/thermoelectric hybrid generator by using a GaAs-based single-junction solar cell and a commercial TEG and compared the efficiencies of the PV-TEG hybrid system with those of the PV cell alone. Li et al. [12] indicated that the load resistances of the TEG alone at the maximum power output, TEG in the PV-TEG, and PV-TEG are different. However, this form is not always efficient. Lin et al. [13] found that the efficiency of the PV-TEG system is generally lower than that of the PV cell alone. The other form of PV-TEG coupling systems

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Nomenclature

a	area ratio
A	area, m^{-2}
c	speed of light, $m\,s^{-1}$
e	elementary charge, C
E	energy of photon, eV
E_g	band gap energy, eV
$F_{AM1.5}$	solar radiance heat flux, $W\,m^{-2}\,nm^{-1}$
h	Plank constant, J s
I	electric current, A
i	dimensionless current
j	current density, $A\,m^{-2}$
k	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
K	thermal conductance, $W\,m^{-1}$
K_B	Boltzmann constant, $J\,K^{-1}$
l	lengths, m
N	number of thermoelectric couples
P	power output, W
q	heat flow, W
q_n	net heat flow, W
r	electrical resistivity, Ω m
R	electrical resistance, Ω
T	temperature, K
T_1	temperature of the hot junction, K
T_2	temperature of the cold junction, K
V	voltage output, V

Subscript

a	ambient
c	photovoltaic cell
F	concentrator
g	band gap
in	incoming
L	loss
max	maximum
min	minimum
n	n-type semiconductors
opt	optimization
p	p-type semiconductors
r	radiation
sc	solar collector
t	thermoelectric generator

Greek letter

α	Seebeck coefficient, $V\,K^{-1}$
ε	emissivity
κ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
λ	wavelength, m
σ	Stefan-Boltzmann constant, $W\,m^{-2}\,K^{-4}$

Abbreviation

PV	photovoltaic
SSS	spectrum splitting system
TEG	thermoelectric generator

employs a spectral splitter to divide the concentrated incident spectrum into two or several segments. The simplest method is that the high frequency part of incident spectrum impinges on the PV cell and the low frequency part is transmitted to a thermal collector. Such a solar spectrum splitting form is regarded as a promising method to alleviate the spectral mismatch and can achieve the high efficiency of solar energy conversion [14]. Several studies have been devoted to investigate the performance of this system. For example, Kilm et al. [15] studied the performance of thin-film solar cells by utilizing the solar spectrum splitting technique. Mizoshiri et al. [16] built the spectral splitting PV-TEG hybrid system and found that the total open-voltage of the hybrid solar generator was increased by 1.3% compared to that of the single PV cell. Zhao et al. [17] experimentally divided the solar spectrum into five segments and the measured efficiency of 35.6% was achieved at 2.8 solar concentration factors. However, the multi-band structure increases the complexity of the system and generally results in more energy losses [14], so that the performance of the SSS should be optimized. Bierman et al. [18] optimized the cutoff wavelengths for the three-band spectrum splitting system (SSS) via an entropy minimization method. Kraemer et al. [19] proposed a general optimum cutoff wavelength scheme that the optimum cutoff wavelengths can be determined from the intersections between the spectral efficiency characteristics of the solar cell and the solar TEG. Ju et al. [20] presented a numerical modeling of the two-band spectrum splitting PV-TEG hybrid system with GaAs solar cell and skutterudites $CoSb_3$ TEG and analyzed the effects of the cutoff wavelength, solar concentration factor, and heat transfer coefficient on the electrical and thermal performances of the system, but the effects of the area ratio of the collector of the TEG to the PV cell on the system have not been considered. Bjørk et al. [21] studied the theoretical maximum efficiencies of the unconcentrated PV-TEG system for the integrating system and the spectrum splitting system and found that the maximum efficiencies of the integrating and spectrum splitting systems are 36.8% and 34.1%, respectively, but the relationship between the efficiency of the PV cell and the temperature has not been given in the spectrum splitting system and the area ratio of the collector of the TEG to the PV cell has not been considered. Previous studies mainly emphasized on optimizing the cutoff wavelengths rather than the performance of the full system. The optimization of the full SSS and the area ratio of the photovoltaic cell to the thermal collector have not been studied. The areas of the thermal collector and the photovoltaic cell strongly affect the performance of an SSS. If the area of the thermal collector is too small, the TEG cannot work normally. If the area of the thermal collector is over large, the net heat flow output does not meet the heat required by the TEG. Therefore, researches on the optimization of the area ratio of the thermal collector to the photovoltaic cell and the full SSS are important for the development of high efficiency SSSs.

In this study, an updated model of the concentrated solar spectrum splitting PV-TEG system is established, in which the concentrated solar spectrum is divided into two segments according to the band gap energy. The parameters of the SSS are optimized. The impacts of the area ratio of the collector-photovoltaic cell on the power output and efficiency of the SSS are discussed in detail. The maximum efficiencies of the SSS and the single solar concentrating photovoltaic cell are calculated and compared.

2. Model description

Fig. 1 shows the energy flow diagram of the concentrated solar spectrum splitting PV-TEG system composed of a concentrator, a splitter, a photovoltaic cell, a solar collector, and a thermoelectric generator. In Fig. 1, q_{in} is the total incoming solar energy, q_c and q_t are the energy gained by the PV cell and the collector, $q_{r,c}$ is the radiative loss due to radiative recombination in the PV cell, q_1 is the heat flow