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Feasibility and parametric evaluation of hybrid concentrated photovoltaic-thermoelectric system

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HIGHLIGHTS

- A coupled model studies effect of critical design parameters in CPV/TEG system.
- CPV/TEG with current thermoelectric materials is more efficient than CPV cell.
- TEG's contribution in total electrical power increases at high sun concentrations.
- More efficient heat sink enhances exceed heat conversion into electricity by TEG.
- Optimal heat transfer coefficients which offer minimum energy cost are found.

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ABSTRACT

Concentrated photovoltaic (CPV) system integrated with thermoelectric generators (TEGs) is a novel technology that has potential to offer high efficient system. In this study, a thermally coupled model of concentrated photovoltaic-thermoelctric (CPV/TEG) system is established to investigate feasibility of the hybrid system over wide range of solar concentrations and different types of heat sinks. The model takes into account critical design parameters in the CPV and the TEG module. The results of this study show that for thermoelectric materials with $ZT \approx 1$, the CPV/TEG system is more efficient than CPV-only system. The results indicate that contribution of the TEG in power generation enhances at high sun concentrations. Depending to critical design parameters of the CPV and the TEG, there are optimal values for heat transfer coefficient in the heat sink that offer minimum energy cost.

1. Introduction

A key advantage of concentrated photovoltaic (CPV) technology is the small active cell area carrying high potential for future cost reduction of the solar energy. More than half of irradiated solar energy transforms to heat in the CPV systems and needs to be removed from the system, while high sun concentration on the small area creates challenges in controlling their temperature. Thermoelectric generator (TEG) is able to utilize a fraction of the otherwise wasted long wavelength thermal energy into useful electricity. During the last decade, several studies have investigated viability of combining photovoltaic (PV) systems with TEG to utilize wasted thermal energy produced by the PV system [1–5]. Primary studies on concentrated thermometric-photovoltaic (CPV/TEG), where PV cells with different band gap values integrated with different thermoelectric materials, [6,7] confirm increment in the electrical efficiency by the hybrid system, and show that the proposed system could be practical.

Zhang and Xuan [8] introduced an advance photon management approach that provides photons transmittance with higher wavelengths in range of 1.1–2.5 μm for the TEG. Therefore the temperature rise in the PV system can be reduced below 50 °C, while performance of the TEG enhances.

According to an irreversible model for a traditional single-junction PV system by Lamba and Kaushik [9], optimum sun concentration ratio should be explored in order to maximize power output of the hybrid system. Lin et al. [10] determined optimum operating regions of hybrid PV/TEG system based on structural parameters of the TEG and operating conditions of the PV. The effective range of photovoltaic' s temperature coefficient (β) has been recognized as an important design parameter. It is shown that [11], when β is bigger than the temperature coefficient at the reference temperature condition, so called critical temperature coefficient, the maximum efficiency of the hybrid system is smaller

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Nomenclature

A	area, m^2
a	areal cost of TEG module, USD/m^2
C	cost, *USD*
b	width of thermoelements, m
EC	energy cost, USD/W
f	thermoelectric fill factor
G	solar radiation, W/m^2
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	length, m
P	power, W
Q	heat loss/ heat transfer, W
T	temperature, K
ΔT	temperature difference, K
v	volumetric cost of TEG module, USD/m^3
W	width of TEG module, m
X	sun concentration
x	length in heat transfer direction, m
ZT	figure of merit

Greek symbols

α	Seebeck coefficient, V/K
β	temperature coefficient, $\Delta\eta/\Delta T$, 1/K
ε	emissivity
η	conversion efficiency
ρ	electrical resistivity, Ωm
σ	Stefan-Boltzmann constant, W/m^2 K^4

Subscripts

1, 2	empirical constants
a	ambient
b	bottom
c	cold junction
cl	conductive layer
cr	ceramic
CPV	concentrated photovoltaic
h	hot junction
hs	heat sink
ic	interconnector
max	maximum
rad	radiation
ref	reference
sky	sky
sp	solder paste
t	top
TEG	thermoelectric generator
+	the top boundary surface
−	the bottom boundary surface

than that of PV-only system, and the hybrid design loses its practical sense.

Beeri et al. [12] reported that hybrid CPV/TEG system has a potential to have more than 50% conversion efficiency with more advances CPV cells and thermoelectric materials. They experimentally demonstrated that electrical contribution of the TEG increases when the sun concentration and, hence, the system temperature rises. A simple PV/TEG model developed by van Sark [13] indicates that efficiency enhancement up to 23% is achievable with thermoelectric materials with $Z = 0.004\ \text{K}^{-1}$. A study by Park et al. [14] on viability of lossless coupling between PV and TEG show that efficiency of the PV device can be further improved up to 30% with a 15 °C temperature difference between hot and cold junctions of the TEG.

TEG can acts as a heat pump to boost power generation of the photovoltaic module; up to 39% as reported by Dallan et al. [15]. It is able to diminish the dark saturation current in the PV module by converting the PV module's waste heat into an electromotive force and ensures better conversion efficiency. TEGs in a CPV/TEG can significantly improve performance of the system with $0.88\ \text{W/cm}^2$ electrical power added to the system at sun concentration equal to 270 [16]. Liao et al. [17] provided some useful criteria for optimal parametric design of the hybrid CPV/TEG system varying with the device output current. However, the results cover only low sun concentrations.

From economy perspective, Kossyvakis et al. [18] show TEGs with shorter legs lessens temperature of the PV system and enhances power output of the hybrid system. However, optimal leg length is restricted to contact resistance value between the TEG elements [19]. Among practical parameters on efficiency of a hybrid CPV/TEG system, temperature is a dominant factor [20] that can be controlled by optimization of the convective heat transfer coefficient and the sun concentration.

The CPV/TEG hybrid system technology still faces some commercialization challenges. The cost of CPV cells is prohibitively high, and Bismuth Telluride based thermoelectric materials suitable for this application are expensive [21]. Nevertheless, the concept of this hybridization significantly reduces amount of the used thermoelectric materials and the cost of the heat sink due to the small operating area. Rather than hybridization with PV systems, TEGs are beneficial candidates for CPVs where higher hot junction temperature is available. Minimization of TE material mass has been considered as a critical feature of specific power generation (ratio of generated power over used mass). It is shown that a single stage TEG can be more efficient costly than two or more stages TEG in term of the specific power generation [22].

In conventional PV/TEG modules the TEG has a minor contribution in power generation, and price of energy production turns to be much higher than a PV-only system. Results [23] show that there is a large difference in cost of daily energy production between a commercial PV and hybrid PV/TEG modules, and in economic perspective the hybrid system is not able to compete with the PV-only module.

To limit rise of the CPV temperature and to achieve high exergetic efficiencies, heat removal by a working fluid in a heat sink is essential and plays a crucial role [24]. Da et al. [25] recommended that powerful temperature control techniques are required for applying high sun concentrations. Effect of convective thermal resistance in a heat sink on power generation of a PV/TEG system is investigated by Najafi and Woodbury [26]. Chen et al. [27] showed that water cooling results higher net power by a solar TEG due to its higher specific heat capacity compared to air cooling. Moreover, Wu et al. [28] found that efficiency of the hybrid system enhances by using nano-fluid cooling technology instead of water cooling.

CPVs have a temperature-dependent performance where the electric conversion efficiency drops with increment in the operating temperature [29]. In order to enhance the temperature distribution on the CPV system an efficient heat sink is compulsory. However when the price of the heat sink is taken into account, there must a balance point for design of the heat sink. Moreover, a heat sink with higher heat transfer coefficient is able to create