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Thermodynamic evaluation of irreversibility and optimum performance of a concentrated PV-TEG cogenerated hybrid system

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ABSTRACT

In this paper, the thermodynamics evaluation of an irreversible CPV-TEG cogenerating system, having Siemens SP75 PV module and commercially available Bi_2Te_3 TE module, has been investigated for wide solar spectrum to encompass the winter and summer solar radiation. Modeling and simulation of the hybrid system has been carried out to understand the feasibility of the system and to determine the irreversibilities present in the hybrid system. The irreversibilities or exergy destruction caused by the irreversible conversion process of solar energy into electricity are calculated using exergy analysis based on second law of thermodynamics. The various exergy losses occurring in the hybrid system have been calculated using exergy analysis. The effects of the incident solar irradiance varying in a wide range from 100 W/m^2 to 1000 W/m^2, TEG junction temperature ratio, concentration ratio, TEG current, Thomson coefficient, irreversibilities or exergy destruction and the incoming solar radiation exergy have been studied. The results showed that the Thomson effect has adverse effect on the performance of the hybrid system and the irreversibilities increase with increase in concentration ratio, *C*. Further, the power output of hybrid system increases by 86% as *C* increases from 1 to optimum value of 3 and the exergy efficiency is higher than the energy efficiency by 8%. The higher values of the irreversibilities make the system less inefficient and therefore, significant improvements are required because the elevated temperature could result in hot spots formation. The results of this analysis may be helpful in designing of practical CPV-TEG hybrid system.

1. Introduction

The unfriendly nature of fossil fuels to the atmospheric environment leads to colossal push on the research towards renewable energy sources. So far, the solar energy is the most exploited alternative energy source and photovoltaic technology is the widely used for direct conversion of photons from the sun into electricity. However, the photovoltaic module efficiency decreases as the PV cell temperature increases (Ito et al., 2017; Deng et al., 2013; Goswami et al., 2000; Sharma et al., 2014, Skjølstrup and Søndergaard, 2016). Since, majority of the infrared region of the solar radiation is converted into waste heat which increases the temperature of PV cell and thereby, reducing its performance and lifetime. Therefore, it is important to control, manage, reduce and possibly utilize this waste heat. As a result, various cooling methods for minimizing the PV module temperature have been applied and some methods are also employed to utilize this waste heat from PV module which results in improvement in PV module efficiency (Sibin et al., 2017; Willars-Rodríguez et al., 2017; Teffah and Zhang, 2017), including the use of thermoelectric coolers, water or air cooling. In addition, the utilization of thermoelectric generators to convert waste heat to electricity has also been studied by many researchers.

Ju et al. (2012) developed a simulation model of a spectrum splitting PV-TE hybrid system with GaAs as PV module and $CoSb_3$ as TE module and optimized the hybrid system using numerical method under different conditions and evaluated the thermal and electrical performance of the hybrid system. Bjørk and Nielsen (2015) examined the performance of PV-TEG hybrid system for four different types of PV modules and concluded that the performance of hybrid system is lower than the PV system alone. The reason for decrease in efficiency of hybrid system is the absence of mechanism for heat removal from cold side of TEG system. Hashim et al. (2016) developed a PV-TEG hybrid model and optimized the geometry of TE module to achieve maximum power output from the hybrid system. The performance of hybrid system is improved as compared to PV system alone. Lamba and Kaushik (2016) developed a CPV-TEG hybrid model and analyzed the performance of hybrid system by including influence of Thomson effect.

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Nomenclature

A	cross sectional area (m^2)
C	concentration ratio
EX	exergy (W)
EX_s	solar radiation exergy (W)
G	incident irradiance (W/m^2)
h	heat transfer coefficient ($W/m^2 K$)
h_0	convective and radiative heat transfer coefficient from top of PV module ($W/m^2 K$)
I	electric current (A)
k	thermal conductivity (W/m K)
K	thermal conductance (W/K)
L	thickness (m)
N	number of thermocouples
P	power output (W)
Q	heat (W)
R	electrical resistance (Ω)
s	Seeback coefficient at (V/K)
T	temperature (K)
U	overall transfer coefficient ($W/m^2 K$)
v	wind speed (m/s)
X_T	TE junction temperature ratio

Subscripts

a	ambient
c	cold side of TE module
con	convection
$contact$	contact
g	glass
h	hot side of TE module
L	load
p	p-type
PV	photovoltaic
R	reflection
ref	reference
rad	radiation
n	n-type
TE	thermoelectric
T	tedlar
S	sun

Greek letters

α_c	PV cell absorptivity
α_T	tedlar absorptivity
β_c	PV packing factor
β_0	cell temperature coefficient (1/K)
ε_c	cell emissivity
τ	transmissivity
ρ	PV reflectivity
ρ_n	n-element electrical resistivity (Ω m)
ρ_p	p-element electrical resistivity (Ω m)
σ	Stefan-Boltzmann constant ($W/m^2 K^4$)
η_c	PV cell efficiency
η_{tot}	hybrid system cogenerated efficiency
η_{PV}	PV system efficiency
η_{ref}	PV reference efficiency
η_{TE}	TEG efficiency
ψ	Hybrid system exergy efficiency
Δ_{irr}	exergy destruction/irreversibility (W)

They determined the optimum concentration ratio to get maximum power from the hybrid system and concluded that the Thomson effect decreases the power output of the hybrid system. Rawat et al. (2017) studied the PV systems from thermodynamic point of view and presented the various models to calculate exergy of solar radiation, defined by several researchers. Li et al. (2017) proposed the one-dimensional model of CPV-TE hybrid system using different PV modules and calculated various exergy losses caused by irreversible conversion of solar radiation into thermal energy. Lamba and Kaushik (2017) carried out the thermodynamic analysis of a trapezoidal TEG including Thomson heat along with Fourier's heat conduction, Peltier heat and Joule heat. They also studied the effects of shape parameter, temperature ratio and load resistance ratio on the power output, irreversibility, energy and exergy efficiency of the TEG system. Wu et al. (2017) analyzed and compared the performance of stand-alone PV system, solar PV-TEG hybrid system and solar PV-TE cooling hybrid system under various conditions and studied the effect of wind speed on the performance of these systems. The PV-TEG hybrid system has the advantage of increased total output power and PV-TE cooling system has the advantage of reducing the temperature of PV cell. Kraemer et al. (2008) developed a method for optimization of hybrid systems for efficient utilization of full solar spectrum to achieve maximum efficiency of the hybrid system and compared the efficiencies of hybrid systems including crystalline silicon, amorphous silicon and heterojunction thin-film PV modules. Zhu at al. (2016) developed and optimized a thermal CPV-TE hybrid system and determined the temperature distribution and heat flow using numerical method. They also developed a model for estimating the economic feasibility of hybrid system and reported the hybrid system high peak efficiency of 23% which is 25% more than that of PV alone (19%) and the thermoelectric generator contributes 648 J of extra electrical energy during the off sun shine hours. Dallan et al. (2015) experimentally investigated the PV-TEG hybrid system to study the feasibility of converting excess PV heat into electricity using thermoelectric generator to improve the overall efficiency of the hybrid system. They reported 39% increment in the efficiency of hybrid system as compared to PV system alone. Da et al. (2016) proposed the approaches for photon and thermal management to enhance the utilization of full solar spectrum solar in PV-TE hybrid systems for both terrestrial and space applications. They reported that in both terrestrial and space applications, the smaller values of concentration ratio are more suitable unless effective approaches for temperature management are used. Zhang and Xuan (2016) carried out the thermal analysis of CPV-TE hybrid system and calculated the temperature distribution and output power in the hybrid system. They also carried out the sensitivity analysis of the hybrid system. Kwana and Wu (2016) developed the thermodynamic model of PV-TEG hybrid system and carried out the dynamical and operational studied in an outer space environment. They optimized the designs of single stage and two stage TEG in terms of mass and power output using multi-objective NSGA-II genetic algorithm. They concluded that the optimal performance of the single stage TEG is better than that of the two stage TEG. Marandi et al. (2018) designed, fabricated and tested the PV-TEG solar cavity-receiver under lab simulated solar radiation and real environment solar irradiance. They reported an efficiency improvement of 18.9% for the hybrid PV-TEG cavity-receiver system as compared to conventional PV-TEG flat plate system and the levelized cost of energy (LCOE) is 9.432 $/kW h which is 67% higher than that of conventional PV-TEG hybrid system. Zhang and Xuan (2017) developed a new PV-TE hybrid system with the arrangement of introducing adjustable cooling blocks to suppress the temperature fluctuations caused by changing solar radiation and carried out experimentation for testing the hybrid system. Kil et al. (2017) fabricated a CPV-TE hybrid system with GaAs based PV module for resolving the thermal degradation problems inthe conventional CPV systems and reported an efficiency increment of 3% in comparison with