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# Improved energy conversion performance of a novel design of concentrated photovoltaic system combined with thermoelectric generator with advance cooling system

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ABSTRACT

Most of the incident solar energy on a PV panel is converted into waste heat. This consequently reduces the efficiency of PV system. Therefore, if certain portion of this waste heat can be utilized adding a thermoelectric generator (TEG) in the PV panel endowed by an efficient cooling system, the output performance of the system can be improved significantly. In this study, a new configuration of nanofluid-based PV/T-TEG hybrid system with cooling channel is proposed to convert certain portion of waste heat to electrical energy in order to improve the overall efficiency of hybrid system. Thus, the nanofluid acts as a coolant and absorbs the heat from the back side of TEG module raising its gradient of temperature, as well as the overall performance of the system. Through a numerical modelling approach, performance of the proposed innovative design has been investigated and compared with the conventional solar-harvesting technology systems. At the optimum value of solar concentration $C$, and maximum operating temperature of 35 Â°C, the obtained results reveal that the electrical energy in NCPV/T-TEG configuration has been found higher by 10%, 47.7% and 49.5% against NCPV/T, CPV and CPV/TEG-HS systems, respectively. Overall, the proposed design of NCPV/T-TEG hybrid system has potential for further development in high-concentration solar systems.

## 1. Introduction

Renewable energy is a promising source of energy as it is clean and environmental friendly compared to fossil fuel-based resources. According to Global Trends in Renewable Energy Investment report, by the year 2017, approximately 55% investment in energy installation was based on renewables energy resources which is roughly more than double invested in fossil fuel based power generation [1]. Several renewable resources are available on earth, and sun is the most promising renewable energy resources to meet the future world energy demand. Energy converter devices that use solar energy as primary resources could be the most effective solution to avoid pollution and reduce the greenhouse effect.

According to the Renewables 2017 Global Status Report[2], about 307.8 GW represent the total electric power capacity generated from the solar energy in 2016. Nearly 98% of this generated power was from PV systems. This is because the annual market of the solar panel witnessed a significant increase nearly to 50%, which rises the global total PV electrical energy to achieve 303GW.

However, PV cells technology faces several technical challenges such as its low performance under extreme weather conditions [3]. Using a solar concentrator technology, the PV cells output enhances, which might reduce the manufacturing [4] and electricity cost [5] of the PV technology. However, under high irradiation, the PV module temperature rises rapidly due to the excess heat, consequently their efficiency drops drastically at elevated temperature. Therefore, removing heat by cooling the PV cells and utilizing certain portion using TEG attached to the PV panels is a crucial approach to boost the energy production in a PV power plant. Several methods and approaches were proposed by researchers to enhance PV cells performance. A summary of these works is available in the review paper published by Makki et al. [6].

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**Nomenclature**

| | |
|---|---|
| $A$ | area, $m^2$ |
| $a_{teg}$ | cross-sectional area of a P or N leg, $m^2$ |
| $C$ | solar concentration |
| $D_h$ | hydraulic diameter, m |
| $e$ | electron charge, $1.6021 \times 10^{-19}$ °C |
| $e_n$ | nanofluid thickness, m |
| $G$ | solar radiation $W\,m^{-2}$ |
| $h$ | heat transfer coefficient, $W\,m^{-2}K^{-1}$ |
| $hr$ | radiation transfer coefficient, $W\,m^{-2}K^{-1}$ |
| $L_c$ | characteristic length, m |
| $l_{teg}$ | height of TEG, m |
| $l$ | collector length, m |
| $\dot{m}$ | mass flow rate, $kg\,s^{-1}$ |
| $n_{teg}$ | numbers of PN junction |
| $Q_{TEG,h}$ | energy that passed in hot side of the TEG, W |
| $Q_{TEG,c}$ | energy that passed in cold side of the TEG, W |
| $R$ | thermal resistance, $kW^{-1}$ |
| $r_{teg}$ | electrical resistivity of P or N junction, Ωm |
| $T_{am}$ | ambient temperature, K |
| $T_{teg,h}$ | hot side temperature, K |
| $T_{teg,c}$ | cold side temperature, K |
| $V$ | velocity, $m\,s^{-1}$ |
| $ws$ | wind speed |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | absorption coefficient |
| $\alpha_{teg}$ | Seebeck coefficient, V/K |
| $\beta'$ | temperature coefficient, $K^{-1}$ |
| $\Delta T$ | temperature gradient, K |
| $\Delta_x$ | spatial step, m |
| $\varepsilon$ | emissivity |
| $\eta$ | efficiency |
| $\tau$ | transmittance |
| $\lambda$ | wavelength, $\mu$m |
| $\o$ | volume fraction |

*Subscripts*

| | |
|---|---|
| $a$ | air gap |
| $c$ | cover glass |
| $n$ | nanofluid |
| $am$ | ambient |
| $p$ | plate |
| $bc$ | back cover |
| $eq$ | equivalent |

*Abbreviations*

| | |
|---|---|
| *PV* | Photovoltaic |
| *TEG* | Thermoelectric Generator |
| *PV/T* | Photovoltaic/Thermal |
| *PV/T-TEG* | Photovoltaic/Thermal-Thermoelectric Generator |
| *NCPV/T* | Nanofluid-based Concentrated Photovoltaic/Thermal |
| *NCPV/T-TEG* | Nanofluid-based Concentrated Photovoltaic/Thermal-Thermoelectric Generator |
| *HS* | Heat Sink |

The thermoelectric conversion system is another alternative mechanism to generate electricity using low grade heat. It allows the generation of a clean electricity from a source of heat through a thermoelectric generator device under Seebeck effect, i.e. presence of gradient of temperature is required. Serval researchers' published works recommended hybrid PV modules and TEG in one system device. Thus, the TEG is placed in the back of the PV cells to absorb and convert the excess heat to electricity. This modus operandi is a unique approach to maximize the overall conversion efficiency of PV system.

Sark et al. [7] conducted a study on PV module under high irradiance condition. The PV cells temperature reached 60–80 Â°C in their study. By integrating a TEG module in the backside of the PV module, authors noticed an improvement of 8to23% on the efficiency of the PV system, depending on the proprieties of TEG materials used.

Lin et al. [8] analyzed the effect of solar irradiance, load resistances and the TEG parameter on the performance of a PV/TEG hybrid system. The TEG module was used to improve the conversion efficiency of solar energy as well as to increase the electrical power output. Kossyvakis et al. [9] examined theoretically and experimentally the electrical output of a PV/TEG hybrid system. By using a TEG device with a thermoelement geometry, the overall performance improvement was achieved 22.5% and 30.2% for poly-Si and dye-sensitized solar cells, respectively. Zhu et al. [10] combined PV/TEG modules to reduce the energy losses in the PV system. Authors found that the overall efficiency of the hybrid system achieved 25%, while the electrical efficiency of the PV module alone, i.e. without TEG module reached 19% only.

Li et al. [11,12] investigated theoretically and experimentally a PV/TEG hybrid system. The PV module and the TEG generator were connected by using a micro-channel heat pipe for heat removal purpose. To increase the gradient of temperature between TEG's both sides, a heat sink was placed in the TEG's cold side. A comparison in terms of electrical performance between the proposed PV/TEG and a conventional PV module under deferent ambient conditions was reported as well. Under the concentration ratio of 8x, and wind speed of 8 m/s, the electrical efficiency of the TEG device improved by 0.82%based on $\Delta T$ = 59.6 °C. This resulted in a significant increase in overall electrical output of the hybrid system compared to the conventional PV system.

Mohsenzadeh et al. [13] designed a novel hybrid PV/T system combined with a TEG generator to increase the overall system efficiency. In addition, a parabolic concentrator was used to intensify the solar radiation. The overall efficiency of the CPV/T-TEG system found to be 60% and 47.30% with and without the glass cover, respectively. Thermal energy represented 90.53% of the total generated power, while electrical energy represented 94.7% only. The TEG generator provided 3.3% from the total generated electrical energy. Soltani et al. [14] proposed a new cylindrical PV/TEG system operated under parabolic through collector. Water was used for cooling with the mass flow rate 0.03kg/s. Authors found that the TEG generator provided only 2.3W from the total 22.714W electrical power delivered by the whole system.

Previous studies have proved the feasibility of combining PV with TEG technology as a hybrid system, however, several literature works highlighted that the combining PV with TEG generator is economically ineffective approach compared to conventional PV generator systems [11,15] due to; low energy conversion efficiency of TEG technology ( 6–8%), limitation of the amount of generated power at low gradient of temperature [16], higher cost of the high end TEG module and the large cooling equipment cost. In addition, most of PV/TEG hybrid system using heat sink as cooling system are non-uniform in the cooling process due to the fact that heat sink relies on the ambient conditions i.e. it achieves higher performance only during windy days. Furthermore, some of the PV/TEG systems use water as a coolant, however water as well has some limitations in its thermophysical properties particularly under high working temperature. This is to conclude that PV/TEG performance is highly depending on the quality of cooling process.

Ideally, TE material should have a large seebeck coefficient, high electrical conductivity and a low thermal conductivity. In the real-