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The theoretical performance evaluation of hybrid PV-TEG system

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ABSTRACT

The concept of co-power generation from the excess heat is a rapidly developing technology due to different material innovations in the field of Thermoelectric Generators (TEGs). The photovoltaic (PV) module subjected to solar irradiation utilizes photon energy but also absorbs the heat energy. The module heat is utilized to generate power by the co-generation devices such as TEG. In this paper, theoretical analysis of hybrid PV-TEG system is analyzed using different analytical methods. The performance of PV-TEG system is estimated using mathematical models of PV and TEG using MATLAB/SIMULINK environment. In this work, a novel non-concentrated flat plate PV-TEG configuration is proposed by using the multi crystalline PV connected in rear side with the Bismuth Telluride TEG. The proposed configuration results in production of 5% additional energy with an increase in overall efficiency of 6% at STC conditions. The TEG in the configuration provides cooling for the PV system and also contributes energy of 1–3% of PV rating. The efficiency of proposed PV-TEG configuration is compared with that of standalone PV by making changes in irradiation and ambient temperature.

1. Introduction

The power sources in the world are changing rapidly towards renewable energy. Out of all the renewable sources, the Photovoltaic (PV) gains more attention in the power generation, because of its advantages such as clean-green energy, no mechanical rotation parts and an abundant amount of input energy. But the amount of input gained by the PV sources is not utilized to its maximum. The PV uses only the light emitted energy to produce electrical power and heat pipes use only the thermal energy to produce hot water/air according to the application. The combination of heat and light energy utilization in a single module is initiated by the hybrid PV-Thermal systems [1].

In the PV-Thermal systems, the coolant in the system creates the effects on the semi-conduction material properties in PV [2]. There are several hybrid configurations in PV-Thermal systems are designed such as hybrid PV with Phase Change Materials (PCM) [3], Nano fluid-based PV-Thermal systems [4] and PV-Thermoelectric Generator (TEG) [5]. Out of all those systems, the PV conjunction with TEG gains more attention in recent years [6]. The recent developments in TEG materials [7] are made co-generation with the PV system for the low-grade heat power sources. The concentrated type PV-TEG configuration are popularly used to capture maximum energy from the both PV and TEG systems [8,9]. But the concentrated type configurations, increase the level of complexity during the installation and maintenance. The research in flat plate PV system with the TEG is in developing stage as a commercial product for domestic users.

The performance analysis of PV-Thermal systems is analyzed with respect to different measures like Coefficient of Performance (COP), overall efficiency and energy & exergy studies. The efficiency of the PV system majorly depends on the irradiance and module temperature [10]. The efficiency of the TEG majorly depends on the temperature difference between the two junctions [11]. Hence the overall efficiency of hybrid PV-TEG configuration majorly influenced by the irradiance and temperature. The excess amount of energy generated for the same input irradiance leads to increase in overall efficiency of the system [12]. There are different hybrid PV-TEG configurations proposed by the authors in [13–16]. It shows that the hybrid PV-TEG configuration generates additional energy so that the overall efficiency increases from 3% to 14% as compared to the standalone PV system.

The theoretical performance analysis of PV-TEG configuration by the [17–19] are for the generalized conditions of different crystalline PV with TEG systems. In [17], the author made a theoretical analysis of forced convective cooling fed hybrid solar thermoelectric generator and it generates additional energy of 4.7 W with an electrical efficiency of 1.2%. The author [20] made a theoretical model of flat plate PV-TEG configuration the electrical efficiency of the crystalline silicon PV is 14.03% and TEG with an efficiency of 5%. Cotfas et al., made a simulation in LABVIEW environment of flat plate PV-TEG configuration and it achieves power gain of 7% with an overall efficiency of 18.93% [21]. Deng et al., simulated the thin film solar cells PV modules with heat

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Nomenclature

Symbol	description (unit)
ζ	temperature coefficient of PV efficiency (%/°C)
ZT	figure of merit
$\tau\alpha$	transmittance-absorption coefficient (–)
α	Seebeck coefficient (V/K)
ρ	thermal resistivity (Ω-m)
γ	thermal conductance (w/K)
T_H	hot side temperature of TEG (K)
T_C	cold side temperature of TEG (K)

Abbreviations

PV	photovoltaic
PCM	phase change materials
PV/T	photovoltaic thermal
R_C	thermal contact resistance
TEG	thermoelectric generator
PV-TEG	photovoltaic-thermoelectric generator
DSSC	dye-sensitized solar cell
c-Si	crystalline silicon
pc-Si	poly-crystalline silicon
a-Si	amorphous silicon
CIGS	copper indium gallium selenide
GaAs	gallium arsenide
CdTe	cadmium telluride
BIPVT	building integrated photovoltaic thermal

collectors connected TEG modules integrated to enhance the amount of power generated. The power generated by the hybrid system is twice higher than the single silicon solar cell [22]. Verma et al. implemented simulation models of PV-TEG system in the MATLAB/SIMULINK with two individual MPPT controls to extract the maximum power the hybrid system [23]. Kwan et al. implemented a simulation model of PV-TEG with Lock on Mechanism (LOM) maximum power control strategy for the configurations [24]. Guiqiang et al., made a theoretical analysis of flat plate PV-TEG load electrical resistance with respect to the internal electrical resistance. The crystalline solar cell maximum efficiency occurs at TEG internal resistance of 0.47 Ω and load electrical resistance of 0.75 Ω. For the Gallium Arsenide maximum efficiency occurs at TEG internal resistance of 2.0 Ω and load electrical resistance of 1.6 Ω [25]. In [22–25], the authors majorly concentrated on the extraction maximum power from the panel by the different controls strategies applied on load side of the system. In this work, we made an attempt to analyze the performance of the system with respect to input parameters such as irradiance and temperature for a novel design PV-TEG configuration. The amount of power generation is maximized by the system design configurations parameters such as glazing, PV material, absorber plate and the type of TEG, number of TEGs, and location of TEG [26]. The Maximum power extraction of the any system configuration with a unit time will lead to generate maximum amount power from that system. So that, the maximum power generated with respect to solar inputs has to analyze with respect to overall efficiency of the system.

The research in the field of TEG alloys materials are moving rapidly to generate the maximum amount of power from the low-grade heat sources [27] and the amount of energy contributed by the TEG is increased from 1 to 10% of PV rating [28]. The feasibility of TEG with the PV made the system are more reliable and economical [29]. But some of the research gaps in the PV-TEG configuration are main constrains for the development of commercialized product and are (i) lack of energy-based studies with respect to each parameter, (ii) The optimum location and rating of TEG are suitable to integrate PV system, (iii) The optimum number of TEGs to connect for the PV system. This work helps to fill the gap in the energy studies of the proposed configuration with respect to the change in irradiance and ambient temperature.

In this paper, we consider a commercial multi crystalline flat plate PV with commercial TEG and integrated it on the rear side of PV made of a copper absorber plate. The mathematical models of PV and TEG modules are implemented in MATLAB/SIMULINK environment. The Fireworks algorithm is used for the estimation of PV parameters, and analytical method used for the estimation of TEG parameters. The combined performance of PV-TEG are analyzed for the change of irradiance and the ambient temperature. The novelty of this work is, it is a proposal a non-concentrated type flat plate PV-TEG configuration integrated with commercial PV and TEG modules. The MATLAB environment is used to simulate the commercial PV and TEG modules and, an optimization technique is used for estimating the unknown parameters of PV. The combined PV-TEG configuration performance is analyzed with respect to the different inputs such as irradiance and ambient temperature.

This paper is organized as follows; Section 2 describes the mathematical modelling of PV and its thermal behavior, Section 3 describes the mathematical modelling of TEG, Section 4 describes the theoretical performance analysis of PV-TEG configuration with respect to irradiance and temperature and Section 5 describes the results and the discussion.

2. Modelling of PV

The performance of the PV-TEG system majorly depends on the PV system. The amount of power generated by the PV will decrease with the increase of heat above the Standard Test Conditions (STC), which will be indicated as a temperature coefficient of power in the manufacturer data sheets. Here we are considering a multi crystalline solar cell and the data sheet shown in Table 1.

To understand the accurate behavior of the selected module, we need to simulate the module by estimating the parameters.

2.1. Double diode modelling

The mathematical model of PV system can be done for two different analogies one is single diode model and another is double diode model. Most of the PV models are single diode models, because, the unknown parameter extraction can be done easily, and it takes less computational time to parameters estimation. The double diode model produces more accurate results than the single diode model by considering the recombination losses of the system [31]. The I-V curves produced by the double diode model more accurate during the low irradiation conditions. The double diode model of the solar cell is shown in Fig. 1.

By applying the Kirchhoff Current Law for the equivalent circuit

$$I = I_{ph} - I_{d1} - I_{d2} - I_p \quad (1)$$

Table 1
Datasheet values of Kyocera – KC200GT 215 module [30].

Parameter	Value
Open circuit voltage (V_{oc})	32.9 V
Short Circuit current (I_{sc})	8.21A
Temperature coefficient of voltage	$-1.23 * 10^{-1}$/°C
Temperature coefficient of current	$3.18 * 10^{-3}$/°C
Area of the solar cell (A)	2612.5 cm^2
Efficiency (η) at STC	17%
Fill Factor	0.74

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