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RESEARCH PAPER

Energetic and exergetic analysis of solar photovoltaic-thermoelectric generator hybrid system

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Abstract : The objective of present study is to determine the energy and exergy performance of the developedSolar Photovoltaic-Thermoelectric generator hybrid system. The experimental setup was examined under Udaipur climatic conditions (24°352 73 N; 73°422 453 E). The hybrid systems convert sunlight into electric power by the PV module and then utilize the rest thermal energy by the TEG module. Based on the first law of thermodynamics, the energy analysis is used to evaluate the output performance of the hybrid system. And the output electric power of the hybrid system is calculated. Moreover, the second law of thermodynamics is applied to the exergy analysis of the hybrid system. The exergy losses caused by the irreversible process of solar radiation converted into electric power and thermal energy are evaluated. The calculation results demonstrate that exergy of system follows the incident solar radiation and most of the input exergy has been lost at output with maximum losses occur when solar radiations are converted into heat.

Key Words : Solar PV, TEG, exergy

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INTRODUCTION

Solar energy being available in abundance at most part of the earth's surface is considered as the most common source of energy. For this solar cells are used for directly converting this solar radiation into electric power. The efficiency of conversion depends on the type of cell used (Green *et al.,* 2015). Although the cells absorb most of the incident radiations but they are able to convert only a fraction of it into electricity and most of the energy is dissipated as heat which further increases the cell temperature (Du *et al.,* 2012). To reduce the effect of temperature on output power of PV system its cooling is essential and Thermo-electric generators (TEG) due to Seebeck Effect are able to convert thermal energy into electric power. Hence these TEG's can be used to extract the heat produced in PV system and generate additional power.

The performance of the PV-TE hybrid system has been investigated by many scholars. Liao *et al.* (2014) established a theoretical model of concentrated photovoltaic thermoelectric generator (CPV-TEG)

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system with low concentration ratio can provide more electric power. The effects of the load resistances and structure parameters of the TE module on the output of the PV-TE hybrid system were analyzed (Lin *et al.,* 2015). The feasibility of the PV-TE hybrid system has been investigated (Energy Conversion and Management). The output electric power of the hybrid system is proved and can reach the sum of the maximum output electric produced separately by PV cell and TE module (Van Sark, 2011). A hybrid system comprised of thermoelectric module and a heat pipe-based photovoltaic/thermal (PV/T) module was proposed (Park *et al.,* 2013). A hybrid system, consisting of photovoltaic cells, thermoelectric modules, and hot water, has been designed to enhance the utilization of solar energy (Makki *et al.,* 2016). And the similar theoretical hybrid system model is established (Yang and Yin, 2011). The CPV–TEG hybrid system models are developed for investigating the influences of conduction, convection, radiation heat losses, thermal resistances, and glass cover on the performance of the hybrid systems (Najafi and Woodbury, 2013; Lamba and Kaushik, 2016 and Zhang and Xuan, 2016). The optimized thermal management is used to promote the output efficiency of the thermal concentrated PV-TE hybrid system (Wu *et al.,* 2015). A tandem PV–TE hybrid system employing poly-Si and dye-sensitized cells was examined experimentally without concentrating sunlight (Zhu *et al.,* 2016). An experimental of the PV-TE hybrid system with concentrated sunlight has been conducted, and show that more advanced PV cells and TE materials used in the hybrid system has a potential to exceed 50% total efficiency (Kossyvakis *et al.,* 2016). These previous admirable efforts have been done based on the energy conservation principle and focused on the energy efficiency of the hybrid system.

Taking the following considerations, an experimental investigation was carried out toutilize the waste heat generated in Solar PV module by integrating it with a Thermoelectric generator under climatic conditions ofUdaipur region and analyze its energy and exergy.

Material and Methods

System Description:

The experimental investigation was carried at theDepartment of Renewable Energy Engineering, Maharana Pratap University of Agriculture and Technology,Udaipur (Rajasthan) India (24°352 73 N; 73°422 453 E) and at an altitude of 582.5 m above meansea level). The study was performed in the month of May under the real atmospheric conditions. The Solar Photovoltaic-Thermoelectric Generator hybrid system consists of a 5W Solar Photovoltaic module, 6 Thermo-electric Generator modules, and toothed fin typeheat sink. In this hybrid system the series connected TEG modules are sandwiched between PV module and Heat sink.

The hot side of the TEG assembly was thermally attached at rear side of PV module while the cold side of the TEG assembly was attached to the aluminum heat sink. The technical specifications of solar panel used are presented in Table 1 and the specifications for commercially available TEG module used are presented in Table 2. The values of input parameters used for further analysis of the hybrid system are given in Table 3.

Table A : Specification of the PV system

Parameter	Value
Number of Cells	18
Type of Cells	Polycrystalline
Maximum Power (P_m)	5
Maximum Power Voltage V_m	17.8 V
Maximum Power Current I_m	0.28 A
Open Circuit Voltage V_{oc}	22.3 V
Short Circuit Current I_{sc}	0.3 A
Fill Factor (FF)	0.74
Dimensions	24cm x 16cm

Table B : Specification of the PV system

Parameter	Value
Dimension	40mm x 40mm x 3.6mm
Maximum Operating Temperature, T_{max}	0-150°C
Open Circuit Voltage V_{oc}	4.8V
Current	20°C /0.97 V/225 mA;
	40°C /1.8V/368 mA;
	60°C /2.4V/469 mA;
	80°C /3.6V/559 mA;
	100°C /4.8 V/669mA
Module Resistance	0.323 Ohms
Wire Length	350 mm
Material	Ceramic / Bismuth Telluride

Only a fraction of solar radiation will be converted into electricity by the PV module while most of its part will be converted into heat. The TE modules have the ability to directly utilize this low-grade heat to generate electric power. The exergy balance of the PV-TE hybrid

Table C : Input parameters used for research work	
Input Parameters	Values
Sun Temperature (T)	5780 K
Nominal operating cell temperature (NOCT)	40°C
Boltzmann's Constant (k)	1.38 x 10-23 J/K
Stefan Boltzmann Constant (σ)	5.67 x 10^{-8} $Wm^{-2}K^{-4}$
Emissivity of the front surface of PV module (ε)	0.91
Area of PV module	0.0384 m^2
Area of TEG module	0.0096 m^2

system is defined as (Li et al., 2017),

$$E_{xin} = E_{xout} + E_{xloss} \tag{1}$$

where E_{Xin} is the total exergy input into the hybrid system,

$$Exin = E_{xin\psi S} = GA_{PV\psi S} \tag{2}$$

where A_{PV}= 0.0384m^2 and ψ_S is the exergy efficiency of solar radiation which is crucial to analyze the exergy transferred for the solar energy systems. The exergy efficiency of the solar radiation means the amount of exergy contained in solar radiation. The exergy efficiency of the thermal emission with temperature T is given as (Petela, 1964),

$$\Psi_S = 1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\frac{T_0}{T} \tag{3}$$

where T is considered as the solar radiation temperature, T_0 is the ambient temperature.

As the output of the PV-TE hybrid system is the electric power considered as available work because of the electric power can be absolutely converted into work, so the output exergy of the system will be calculated by

$$E_{out} = E_{XPV} + E_{XTE} = P_{PV} + P_{TE} \tag{4}$$

The net exergy efficiency of the system will be defined by

$$\Psi_{PVTE} = \frac{E_{XPV} + E_{XTE}}{E_{Xin}} = \frac{P_{PV} + P_{TE}}{GA_{PV\Psi S}} = \frac{\eta_{PV} + \eta_{TE}}{\Psi_S} = \frac{\eta_{PVTE}}{\Psi_S} \tag{5}$$

The exergy losses, caused by the irreversibility of the process of the energy conversion in the PV-TE hybrid system includes (Li et al., 2017)

$$E_{Xloss} = E_{Xsur_{loss}} + E_{Xsolar_{loss}} + E_{Xpvte_{loss}} + E_{Xte_{loss}} + E_{XC_{loss}} \tag{6}$$

The first term is the surface loss caused by the heat exchange between the surface of the PV module and the environment. The second term is the exergy loss generated when the high-grade solar radiation is converted into low-grade thermal energy. The third term is caused by the heat transferred from the rear of the PV module to the hot side of the TE module. The forth term is caused by the TE module convert the thermal energy into electric power. The last term is the exergy loss caused by the heat exchange between the cold side of the TE module and the cold plate of heat sink. To maximize the output electric power of the TE module, the temperature of the cold side will be cooled down close to the environment.

Usually, the temperature of the PV module is higher than environment temperature. So the surface of the PV module transfers heat to the environment. According to the efficiency of the Carnot cycle and the definition of the exergy,

$$E_{Xsur_{loss}} = \left[\varepsilon_{PV}\sigma\left(T_{PV_S}^4 - T_0^4\right)\right]A_{PV}\left(1 - \frac{T_0}{T_{PV_S}}\right) \tag{7}$$

where ó is the Stefan-Boltzmann's constant and $å_{PV}$ is the emissivity of the PV module.

As we know that solar radiation converted into electric power and thermal energy by the PV module is an irreversible process, and the exergy loss will be calculated by

$$E_{Xsolar_{loss}} = E_{Xin} - E_{Xsur_{loss}} - E_{XPV} - q_{out}A_{TEC}\left(1 - \frac{T0}{T_{PVR}}\right) \tag{8}$$

whereq_{out} is the heat flux between the PV and TE module and thus the last term of the equation describes the exergy transferred from the rear of the PV module to the TE module.

$$q_{out} = -k\frac{T_H - T_{PV_R}}{\Delta x} \tag{9}$$

where k= 0.3 W/mK is the thermal conductivity of material emitting heat and Δx= 0.0003m is thickness of back sheet of PV module across which heat is being transferred.

The thermal resistance between the rear side of the PV module and the hot side of the TE module not only hinders the heat transfer but also reduces the quality of the energy. This exergy loss will be calculated by,

$$E_{Xpvte_{loss}} = q_{out}A_{TEG}\left(1 - \frac{T0}{T_{PVR}}\right) - q_{out}A_{TEG}\left(1 - \frac{T_0}{T_H}\right)$$

$$E_{Xpvte_{loss}} = q_{out}A_{TEG}\,T_0\left(\frac{1}{TH} - \frac{1}{T_{PV_R}}\right) \tag{10}$$

The TE module recovers the thermal energy from the rear of the PV module, a part of the thermal energy is converted into electric power, and the other parts are rejected from the cold side. The exergy loss in this process will be calculated by,

$$E_{Xte_{loss}} = q_{out}\, A_{TEG}\left(1-\frac{T_0}{T_H}\right) - E_{XTE} - q_c A_{TE}\left(1-\frac{T_0}{T_C}\right) \quad (11)$$

where q_c is the heat rejected to the cold side of the TE module.

$$qc = -k\frac{T_C - T_H}{\Delta k} \quad (12)$$

where k= 1.20 W/mK is the thermal conductivity of material emitting heat and Δx= 0.0036m is thickness of TEG module across which heat is being transferred

As the temperature of the cold side cooled by the cold plate of heat sink will be close to environment temperature. The exergy, which cannot be used in the PV-TE hybrid system, is contained in the heat rejected from the cold side of the TE module.

$$E_{Xc_{loss}} = qcA_{TEC}\left(1-\frac{T_0}{T_c}\right) \quad (13)$$

Results and Discussion

To analyze the energy and exergy of Solar PV and Thermoelectric generator system in actual use under climatic conditions of Udaipur region, an experiment was conducted. The results obtained for the system using formulae presented in materials and methods are presented graphically (Fig. 1–4).

The power produced for Solar Photovoltaic-Thermoelectric Generator Hybrid System is compared with the individual sub systems in Fig. 1. The maximum power produced in hybrid system was 5.25 W at noon.

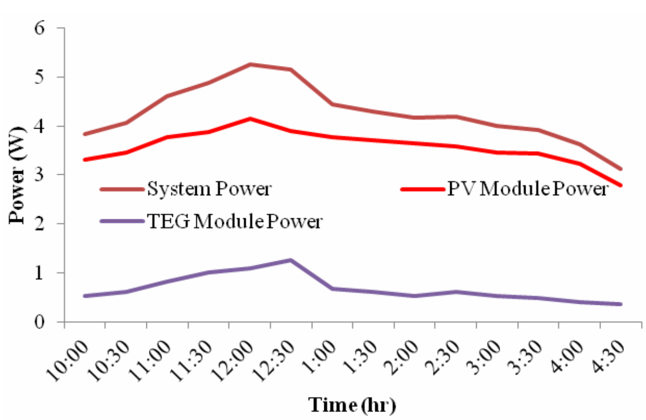

Fig. 1 : Power of Solar Photovoltaic-Thermoelectric generator hybrid system

The average increase in power due to integration of both the PV module and TEG module for hybrid system was 18.5% when compared with only PV producing the power.

For the energy economics of developed system, the energy and exergy analysis of hybrid system was carried out for estimating the quantity and quality of energy respectively. The energy analysis is calculated on the basis of first law of thermodynamics. The exergy analysis is calculated on the basis of second law of thermodynamics and it deal with the evaluation of all the losses occurred within the system due to various parameters related with the system. The energy efficiency was found in the range of 12.9% to 11.3% with average efficiency of 14.09% and exergy efficiency was 13.05% to 11.4% with average efficiency of 14.22%. Figure 2 shows effect of solar radiation on exergy input of hybrid system. It is clear that exergy input curve is following the solar radiation curve it depends on solar radiation and area of PV module collecting the incident radiations.

Fig. 3 shows the input and output exergy of the

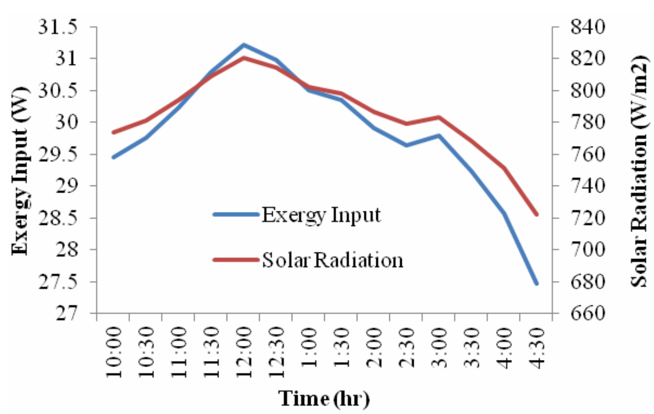

Fig. 2 : Exergy Input and Solar Radiation of Hybrid System

hybrid system. The exergy input for the system was in range of 29.46 W to 27.47 W and output exergy for the system was sum of power produced by both sub systems and it ranges from 3.85 W to 3.13 W. The output exergy increases with increase in input exergy.

It is observed that the exergy received by the system was not completely utilized for power generation and thus it results in very low output exergy. This exergy lost during the conversion was occurred due to the losses within the system. These losses are shown in Figure 4. There were five types of losses occurred in this hybrid

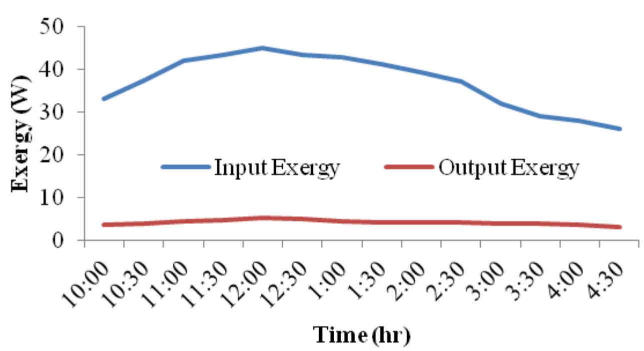

Fig. 3 : Input and Output Exergy of System

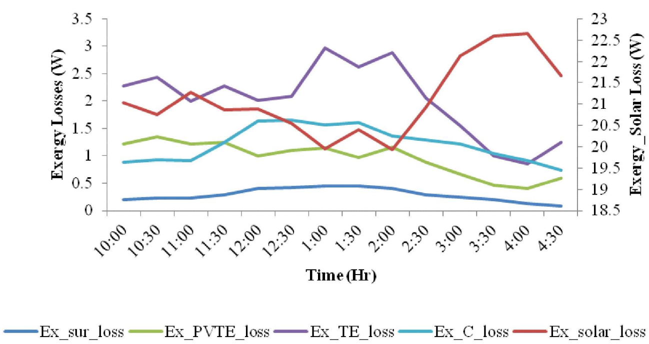

Fig. 4 : Exergy Losses of Hybrid System

system. The first loss is the surface loss caused by the heat exchange between the surface of the PV module and the environment and was very low ranging from 0.2 W to 0.08 W. The second loss is the exergy loss generated when the high-grade solar radiation is converted into low-grade thermal energy and was found to be the highest among all the losses of system with range from 21.04 W to 21.67 W and maximum 22.6 W. The third loss is caused by the heat transferred from the rear of the PV module to the hot side of the TE module and was found minimum ranges from 1.21 W to 0.58 W. The forth loss is caused when the TE module converts the thermal energy into electric power and was second highest after the solar losses with range from 2.27 W to 1.25 W. The last loss is the exergy loss caused by the heat exchange between the cold side of the TE module and the cold plate of heat sink and found to be in range of 0.89 W to 0.74 W.

Conclusion:

Through the direct integration of TEG and heat sink at the rear side of PV module helps in improvement of overall efficiency due to average increase in power of hybrid system when compared with only PV producing the power.

It was observed that exergy depends on solar radiation and area of PV module collecting the incident radiations. Increasing the solar radiation intensity, the exergy efficiency of PV system increases initially and then decreases after attaining the maximum solar radiation intensity. The output exergy of system increases with increase in input exergy.

Due to the losses occurred within the system, the availability output exergy is very low. It was observed that the maximum amount of exergy is lost when the high-grade solar radiation is converted into low-grade thermal energy.

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