Solar Energy 161 (2018) 38–46

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

The experimental investigation of a hybrid photovoltaic-thermoelectric power generator solar cavity-receiver

Omid Farhangian Marandi, Mohammad Ameri*, Behrouz Adelshahian

Mechanical & Energy Eng. Department, Shahid Beheshti University, Tehran, Iran

ARTICLE INFO

Keywords:
Photovoltaic-thermoelectric hybrid
Cavity
Solar power
Overall efficiency

ABSTRACT

In this manuscript, a solar cavity packed with hybrid PV-TEG modules has been designed, fabricated and investigated experimentally. Reducing the re-radiation loss of solar radiative power in a cavity receiver has led to an increase in module temperature. TEG modules convert directly heat into electricity using Seebeck effect induced by a temperature difference between them. They were utilized to decrease the PV module temperature and generate extra power. The device was subjected to a simulated solar radiation of 1000 W/m^2 over its aperture in a laboratory environment. It was also tested under solar irradiance which varied during daily hours. The efficiency of the hybrid system reached a peak of 21.9% at the start of production in the morning when the system was under real sunlight exposure. The significant part of power produced by the PV panels which was strongly affected by the temperature increase, and it consequently caused the efficiency drop despite the solar irradiance and ambient temperature enhancement. However, during the afternoon, as the ambient temperature and solar irradiance decreased, the efficiency increased to 20%.

The measurements of the current and voltage of the system have revealed that the hybrid PV-TEG power generation is three times greater than a flat PV-TEG system power production. The hybrid cavity PV-TEG efficiency improvement has been 18.9% in comparison with the conventional system, whereas the economic analysis of the cavity system has shown that the levelized cost of energy (LCOE) is 9.432 US $/kWh which is 67% greater than the PV-TEG flat plate LCOE.

1. Introduction

Despite more economical options issues such as fossil fuels for electricity generation, renewable energies have attracted much attention in recent years. Also worrying issues such as unsteadiness in fossil fuel prices, the increase in air pollution due to the combustion of fossil fuels in ordinary cars or old thermal power plants have persuaded many researchers to investigate cost-effective approaches for using renewable energy sources all over the world. Solar energy as the most plentiful source of energy on the earth is considered one easy access option. Based on the recent studies in the field of solar energy, many researchers have studied and examined direct conversion of it to electricity using photovoltaic (PV) effects. Although the price of solar energy in comparison with other conventional methods is still high, recent progress in material science and engineering have lessened the costs. Therefore, increasing the efficiency of the PV systems is very significant.

When the PV modules are exposed to solar radiation, the overall efficiency of them decreases as their temperature undesirably increases. The efficiency of the PV modules decreases about 0.5% per every degree of temperature increase (Tonui and Tripanagnostopoulos, 2008). Thus, the PV modules can be considered as a system that produces electricity and also supply heat for another secondary device making the hybrid system more efficient. Thermoelectric generator devices as a converter of any heat source such as solar energy or waste heat directly into electricity, utilize Seebeck effect which induces voltage gradient by the temperature difference between hot and cold surface, has drawn increasing interest in recent decades (Goldschmid, 2009). Regarding thermoelectric devices, many advantages make them suitable to be used with photovoltaic modules as a hybrid system. Having high reliability, not having any moving parts, being environmentally friendly and easy installation have attracted researcher's attention to investigate the practical approaches of thermoelectric device application (Muto, 2011). Zebarjadi et al. (2012) have reviewed perspectives on thermoelectric and in the particular progress made in thermoelectric in recent years. The first developed solar thermoelectric generator efficiency was less than 1% (Telkes, 1954). However, due to rapid advances in the field of material science, solar thermoelectric generators (STEG) are applied in

* Corresponding author.
E-mail addresses: m_ameri@sbu.ac.ir, ameri_m@yahoo.com (M. Ameri).

https://doi.org/10.1016/j.solener.2017.12.039
Received 13 August 2017; Received in revised form 27 November 2017; Accepted 19 December 2017

different solar systems. These systems classified into four types: (i) Non-concentrated STEGs (ii) concentrated STEGs, (iii) Thermal TEG hybrids (iv) Photovoltaic TEG hybrids (Sundarraj et al., 2014). The concept of a coupled thermal and PV converter was taken up by Vorobiev et al. (2006). Their study showed that the concentration of the incoming solar radiation led to an increase in efficiency of 5–10%. Also, Van Sark (2011) proposed to use the waste heat by attaching the thermoelectric generators (TEG) to the back of PV modules to form a CPV-TEG hybrid device.

The additional electricity can be generated by the TEG which is attached backside of PV module, and so the efficiency of the hybrid device can be improved. Fisac et al. (2014) showed that for the same temperature condition, PV-TEG demonstrates an improved performance than a simple photovoltaic system. Ju et al. (2012) study described the contribution of about 10% of the output power for TEG modules in the PV-TEG hybrid system. Wang et al. (2011) developed a dye-sensitized solar cell (DSSC)-TEG model to utilize both the high and low energy photon for energy conversion and achieved efficiency of 13.8%. The first polymer based PV-TEG for power production was developed by Zhang et al. (2013) which produced 9–11 mW/cm^2 power density for the temperature difference of 5–9 °C respectively.

The theory and technology of flat PV-TEG system were discussed and developed extensively during the past years. Moreover, various materials for PV and TEG have been used, and the methodology of efficiency improvement was studied. Chávez-Urbiola et al. (2012) experimentally investigated the feasibility of using thermoelectric generators in non-concentering hybrid systems. According to their results, the thermoelectric generator output was linearly dependent on the temperature difference between the hot and cold thermoelectric plates and reached about 4% at a temperature difference of 155 °C. Also, power generation was directly proportional to the temperature difference with a power of two. The cost-efficiency analysis showed that the PV module and TEG cost would be the same if those devices were used at the industrial level. Deng et al. (2013) developed and tested a hybrid system consisting of thin-film silicon cells, thermoelectric generators, and collectors. They also modeled the thermoelectric generators heat flux distribution using finite element methods. The total production capacity of the system was reported to be 393 mW which was twice the power generated by the solar cell alone.

Park et al. (2013) utilized the crystalline Si PV and a bismuth-tellurium based commercial TEG, which electrically connected in series. Their flat plate hybrid system including a heat sink in cold plate of TEG reached an overall efficiency of 16.3%.

The performance of a flat plate PV–TEG hybrid system, employing poly-Si as well as dye-sensitized solar cells, were examined experimentally by Kossyvakis et al. (2016) by applying LED lamp to provide illumination. Their results demonstrated the hybrid efficiency of 12.4% for poly-Si and 9.3% for DSSC PV module.

A Xenon sunlamp with 804.1 W/m^2 irradiance was used by Dallan et al. (2015) as the solar simulator and the flat pate PV–TE hybrid system exposed to the sunlamp. At this condition, the PV–TEG hybrid system converted 13.2% of the available solar energy into electrical energy.

Using nanomaterials for increased sunlight absorption was another method of improving the efficiency of the hybrid device. Hsueh et al. (2015) applied the xenon lamp as a solar simulator with the irradiation intensity of 1000 W/m^2. Their study showed that covering CuInGaSe2 (CIGS) photovoltaic cells by ZnO nanowire reduced the re-radiation from the cells. The efficiency of the PV alone was 16.5% whereas the total efficiency of the hybrid PV -TEG system was 22%.

In the previous studies as mentioned earlier, the hybrid PV–TEG systems tested under lab conditions which implied a constant solar irradiance near 1000 W/m^2. Under outdoor conditions, the solar irradiance and ambient temperature changed during a day and therefore the power produced by the system changes along a day. Soltani et al. (2017) investigated a photovoltaic-thermoelectric hybrid system using different cooling methods consisting of natural air cooling, forced air cooling, water cooling and also nanofluid cooling with two different mixtures for the cold side of the thermoelectric. The experiment performed at the outdoor conditions under sunlight exposure. The maximum efficiency of the hybrid system was 15.5% at the start of the test in the morning hours by employing SiO2/water nanofluid cooling, which yielded the highest power and efficiency compared with the natural cooling method.

Some researchers have employed the enclosure for reducing heat convection on flat hybrid PV-TEG.

Mohsenzadeh et al. (2017) introduced new design receiver for parabolic trough photovoltaic/thermal collector. A triangular cross section channel with an outer surface covered with monocrystalline silicon photovoltaic and thermoelectric modules is applied as the receiver of this concentrator. This combined heat and power system is installed in the focal distance of a linear parabolic concentrator equipped with a sun tracking mechanism of the polar type. The output power of without cover hybrid system was 1.53% higher than the hybrid system with cover. Performance evaluation of the system shows that daily average electrical and thermal efficiencies can reach 4.83% and 46.16%, respectively.

Zhu et al. (2016) designed a hybrid system with a transparent enclosure and optimal thermal concentration. The developed flat PV-TE hybrid system included nine solar cells with a maximum efficiency of 21.8%. The experimental results under sun exposure showed a high peak efficiency of 23% in the outdoor test which was 25% more than the PV cell efficiency. Their cost-energy analysis indicated that the cost of the hybrid system was equal to the single PV cell cost.

Direct energy conversion by flat PV-TEG systems always have a massive amount of thermal losses due to re-radiation from panel surface and causes the solar to electricity efficiency of the system to decrease. The cost-efficiency analysis of the hybrid systems guides one to find a feasible methodology of efficiency improvement. An appropriate way to minimize the re-radiation is to use the cavity to increase the absorption coefficient of the system (Diver, 1987). Smaller apertures of the cavity reduce re-radiation losses but intercept less solar power in comparison with the open enclosures. Cavity surfaces in a fully open aperture, capture more radiation power and achieve higher temperature and more re-radiation (Steinfeld and Schubnell, 1993).

Suter et al. (2011) designed a solar cavity-receiver packed with an array of thermoelectric converter (TEC) modules and exposed to concentrated solar radiation. The increased TEG efficiency due to the reduction of re-radiation reported.

In this paper, a novel hybrid system is experimentally investigated. A solar cavity-receiver is packed with PV-TEG hybrid modules that are directly exposed to solar radiation. Thus, an experimental setup was developed to study the new system. The significant advantages of the proposed design which have a considerable effect on the system efficiency are:

(1) Efficient capture of solar radiation and remarkable reduction of the re-radiation losses (2) Using the temperature difference between the back side of the PV module and the ambient temperature to produce extra electrical power by TEG modules.

The main contributions of this manuscript can be mentioned as:

- Proposal for a high performance innovative solar PV-TEG hybrid module embedded in cavity receiver.
- Design, fabrication and experimental assessment of the new system.
- Efficient capture of solar radiation and remarkable re-radiation loss reduction.
- Production of extra electrical power by TEG modules and dissipation of the heat generated by PV modules.
- Solar-to-electrical energy conversion efficiency is significantly higher than the PV efficiency.
- Study of the cavity aperture size effect on the module power generation.