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# Recent developments in the design of Hybrid Photovoltaic–Thermoelectric Generators: A Review

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***Abstract***— ***Photovoltaic cells do not convert sufficient amount of solar irradiation into electrical energy. A big amount of solar irradiation is unexploited in the form of thermal energy in case of solar photovoltaic energy conversion system. To make this conversion more efficient and effective, Hybrid photovoltaic and thermoelectric system (PV-TEG) can be used. In this system, there are two types of energy conversion involved. First is converting energy of solar irradiation into electricity by means of photovoltaic system and other is the conversion of waste heat of PV system into electricity via Thermoelectric Generator (TEG). Moreover, hybrid PV-TEG system is environmentally responsive and has no harmful impacts on environment. Hybrid PV-TEG system upturns the total dependability without degrading the quality of power produced. In this manuscript, summary of the prior works regarding progress of technological innovation in the hybrid PV-TEG structures is discussed. The scope for future work in utilizing this technology is also discussed.***

***Index Terms***— ***Hybrid Energy System, Photovoltaic (PV), Thermoelectric Generator (TEG), Waste Heat Recovery***

## I. INTRODUCTION

In a photovoltaic (PV) cell, a big amount of solar irradiation is wasted into thermal energy which upturns the temperature of the PV cell. The reason for this waste heat is absorption of photons having low energy and thermalisation of electrons having high energy and excited state [1]. Besides using cooling method for PV Cells, there can be an approach to utilize this waste heat via thermoelectric generator (TEG) which works on the basis of Seebeck Effect. The advancement of various kinds of PV cells (e.g. dye sensitized solar cells) via thermoelectric generator (TEG) have been deliberated. Previous studies depict valuable information on designing as well as enhancing the performance of the hybrid PV-TEG system. In recent times, a hybrid PV-TEG system comprising of a polymer solar cell has been testified which was located upon thermoelectric generator [2], the experimental analysis of hybrid PV-TEG system depicted that the efficiency of hybrid system is better than using PV or TEG system alone. The basic principles of solar PV and TEG are described as follow-

**Solar Photovoltaic-** The photovoltaic (PV) method directly transforms solar irradiation into electrical energy. In a photovoltaic cell, there are more than one thin films of semiconductors such as silicon, germanium etc. When this semiconductor is exposed facing sunlight, electrical charges are induced which results in direct current flow due metal contact conduction. A number of cells are coupled together to make a Solar photovoltaic panel. The desired value of electrical power can be attained through linking a large number of PV Panels in parallel or series arrangement depending upon the application and expected demand of power output. PV panels requires comparatively less maintenance and its life is long due to less moving parts in PV system. Also, there is no emission of harmful gases as in case of conventional power plant. The process is PV system is virtually silent [3]. These advantages makes PV system a viable technology for electricity production.

**Thermoelectric Generator (TEG)** - These devices works on the basis of Seebeck Effect. According to Seebeck Effect, if two dissimilar metals or semiconductors are linked at two different junction and temperature difference is created between these junctions, a voltage difference is generated across the junction [4]. In this way, thermal energy is altered into electricity via TEG, but the efficiency of this energy conversion is less. Still there are some advantages of thermoelectric conversion as the operation takes place without any noise and without wear. A TEG usually comprises of a moderate number of thermoelectric elements, a thermal energy source at the high temperature side and passive cooling at the low temperature side. The amount of electrical power produced mainly governed by the Figure-of-merit (ZT) value. It is represented dimensionless as:

$$\mathbf{ZT = S^2 \sigma T / k} \quad (1)$$

Where 'S' is Seebeck coefficient, 'σ' is electrical conductivity, 'T' is the temperature of material and 'k' is thermal conductivity [4]. The dependency of figure of merit has been illustrated in the Fig. 2. Saniya LeBlanc [5] demonstrated the work related to the thermoelectric materials, it was depicted that Chalcogenide materials, $Bi_2Te_3$ and PbTe were primarily noticed for thermoelectric operations.

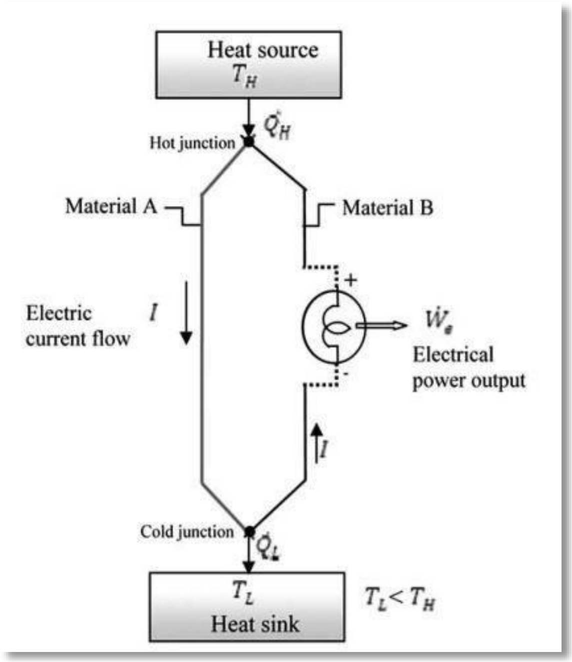


**Fig. 1**. Schematic diagram of Seebeck Effect [4]

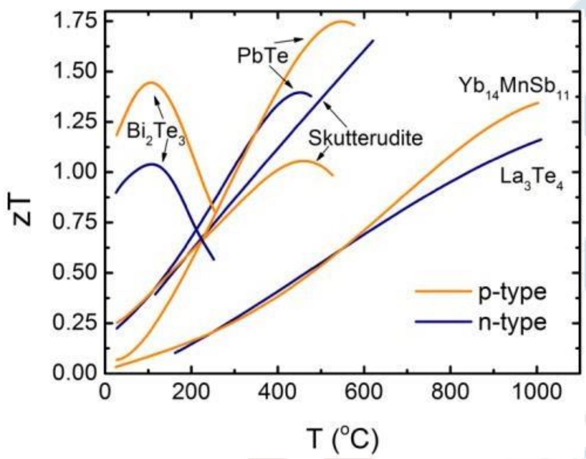


**Fig. 2.** Reliability of Figure of merit (ZT) over Temperatures for various thermoelectric materials [5]

## II. Analysis of Previously Devloped Models of Hybrid PV-TEG System

*Chen J. (1979)* discussed effects of various irreversibility in solar assisted thermoelectric power generation. It was concluded that heat losses to surrounding and at interface surfaces reduce the performance of complete system. Heat losses due to thermal and electrical resistance in the system also decrease efficiency [6]. *Benson & Jaydev et al. (1980)* proposed the use of thermoelectric generators (TEGs) in association with some types of low grade thermal energy such as Ocean thermal energy, geothermal energy and solar pond to generate useful amounts of electricity. In this work, the Carnot efficiency of thermoelectric system was found around 20% only due to less temperature difference across TEG [7]. *Benson & Tracy et al. (1982)* also described the use of TEGs with waste heat. In this work the system design was developed via use of thin film TEG [8].

A. *Steinhuser et al. (1996)* proposed hybrid system with focus on reducing the size of TEG geometries. The system ensured cost-competitiveness via the use of TEGs with greater reliability [9]. Theoretical as well as experimental study of solar assisted thermoelectric generators had been performed by *Omer and Infield (1998)* [10]. Furthermore, *Vorobiev et al., (2006)* offered diverse designs of the hybrid systems. In First design, the sunlight was directly imposed on photovoltaic module and thermoelectric generator. In the other design, the sunlight was directly impinged on PV module only, TEG was operated by the based heat of PV operation. The conversion efficiency was slightly increased in both the cases [11]. *Kraemer et al. (2008)* established a method to optimize the output of hybrid system [12]. The reason for current interest towards hybrid solar systems is due to their greater efficiency and stable performance.

*Zhang et al. (2009)* presented a summary of renewable energy sources with emphasis on TE energy sources and combined TE-PV energy sources. Consequently a new TE-PV energy source was designed and employed for hybrid electrical vehicles. The experimentation confirms that the proposed system can accomplish Maximum Power Point Tracking (MPPT) successfully [13]. The proposed TE- PV arrangement is shown in figure-3.

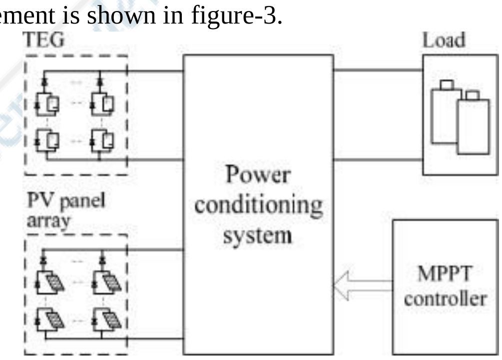


**Fig. 3.** Schematic diagram of Proposed TE-PV System

*Van Sark (2011)* proposed a mathematical model to calculate the efficacy of joint photovoltaic- thermoelectric system. The outcomes indicated that conversion efficiency of the PV system can be upgraded by adding a thermoelectric generator. This combined system augment the conversion efficiency in the range of 8-23 %. There should be sufficient temperature difference across TEG for good efficiency [14].

## III. Recent Developments in Hybrid PV-TEG Systems

*Bjørk et al. (2015)* discussed a simulation model for 4 kinds of feasible photovoltaics and a bismuth telluride (Bi2Te3) thermoelectric generator. The result did not show a viable option for this combined system because the

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performance of PV decreases significantly with increasing temperature. The degradation of electrical energy output of PV system with temperature is quicker than the increase in electrical energy output of TEG. The low efficiency of thermoelectric modules is the main reason for this. Commercial PV cells such as Crystalline Si (c-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS); produced lower power for combined PV-TE system than the PV alone. Only for an amorphous Si (a-Si) cell, the performance of combined system slightly increases. So the combined PV-TE system could not be efficient and effective when it would be a sensor application, i.e. PV cells produces power directly in daylight and TE device produces power in night due to established temperature difference [15]. The system offered in this work is represented in the figure 4.

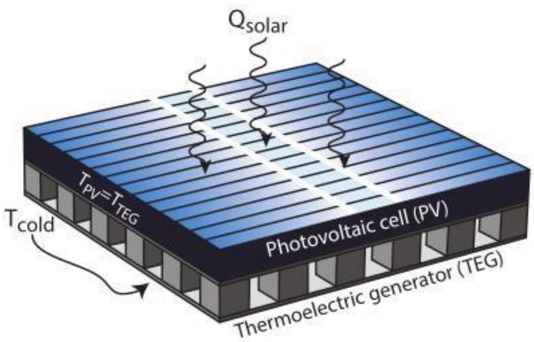


**Fig. 4.** Image of Combined PV-TEG system

Shirin Ahadi et al. (2014) discussed that the efficiency of PV cell decreases at higher temperature. If a thermoelectric generator is coupled with PV cell, it would help in increasing performance of PV module. In this work, a Si PV cell and a TEG of large area were coupled in such a way that TEG was at the rear side of PV Module. The results depicted that efficiency of combined system is 7-11% greater than the efficiency of PV System alone [16].

*Daud et al. (2012)* discussed a prototype of PV coupled with TE modules. The results showed that the conversion efficiency increases slightly if cold side of TEG is cooled using passive liquid cooling. Also the use of Si-Ge or Pb-Te thermoelectric modules can contribute to increase in overall conversion efficiency [17].

Hashim et al. (2016) proposed a model to optimize the dimensions of thermoelectric generators in a hybrid PV-TEG system. In this model, the working temperature of PV cell reduces due to heat transfer into TEG and an additional amount of electricity generated due to established temperature gradient across the two junctions of the TEG. Thus, solar energy is converted into thermal energy and then into electrical energy. 8 types of TE modules were used to analyze the dependency of the output power on the module geometry. To simulate this, a MATLAB program was used. Simulation result showed that the power output of TEG increase up to a certain length. After that if the length of module is increased, power output of TEG decrease. So it is essential to demonstrate a thermoelectric module with the optimum length which enables a TEG to operate at maximum power producing condition. Also larger area and large number of thermo-elements required to increase power output. Thus, the output power of TE module upturns at the expense of material consumption [18].

## IV. PROPOSED MODEL

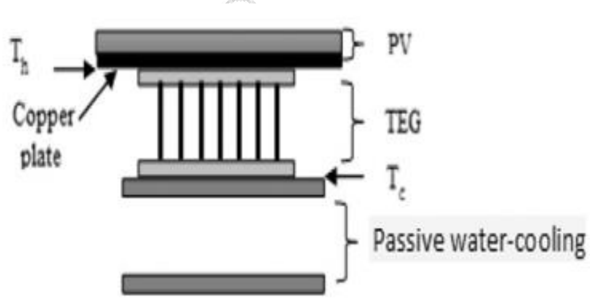


**Fig. 5.** Illustration of the proposed PV-TEG Model

The proposed model for hybrid PV-TEG system is schematically shown in figure 5. In this model, The waste heat of PV system is conducted to the hot side of TEG by means of a copper plate, as thermal conductivity of copper is relatively good (≈ 385 W/m-K). There can be a passive water cooling (e.g. Thermosiphon) at the low temperature side of TEG which helps in making greater temperature difference across TEG. The efficiency of TEG is given by:

$$\eta_{TEG} = \frac{\Delta T}{T_h} \frac{(\sqrt{1+ZT_m}-1)}{(\sqrt{1+ZT_m}+\frac{T_H}{T_C})} \quad (2)$$

Where ΔT - Temperature difference across TEG,
Th – hot side temperature;
Tc - cold side temperature;
Tm - average of Th and Tc
Z- Thermoelectric material property known as figure of merit.

The performance of the PV Cell is also reliant on the cell temperature and is given by:

$$\eta_{PV} = \eta[\mathbf{1} - \boldsymbol{\beta}_0(\boldsymbol{T}_{cell} - \mathbf{298})] \quad (3)$$

Where $\eta_0$ – Efficiency at 25˚C for PV cell (approx. 10%)
$\beta_0$ – Temperature coefficient
$T_{cell}$ – Cell temperature

The heat energy absorbed at the hot side of the TEG can be estimated by subtracting power produced from PV cell and non-absorbing heat losses from the total solar energy available.

$$\mathbf{QTEG} = \mathbf{QSola}(\mathbf{1} - \eta\mathbf{PV}) - \mathbf{Qc} - \mathbf{Qr} \quad (4)$$

Where Qsolar – The total heat available due to solar irradiation,
Qc – Convective heat loss,
Qr – Radiation heat loss

The following expression can be used to estimate the power produced by means of hybrid PV-TEG system can be calculated as follow:

$$Ptotal = Qsolar.\eta PV + QTEG.\eta TEG \quad (5)$$

## V. CONCLUDING REMARKS

It can be depicted that hybrid PV-TEG device is a viable option of waste heat recovery from PV module, but to make this hybrid PV-TEG system a sustainable option, there is a need to work on the following points:

- The research should be focused on developing thermoelectric material of better figure-of-merit (ZT).
- Various losses of heat such as convective heat loss, radiation heat loss through the PV system should be minimized so that the heat flux on the hot side of TEG is more.
- The design of cold side of TEG (heat sink) need to be developed and there should be passive cooling at cold side. In case of active cooling, there will be requirement of power input which result in lesser efficiency.
- It can be seen that thermoelectric modules are linked to produce more power. In such cases, there would be power loss due to module mismatching. The future research should focus on optimization of power loss due to module mismatching.
- Thermal contact resistances must be minimized to increase conversion efficiency.
- There is a need of geometry optimization for TEG, previous researches indicates that the performance thermoelectric module having smaller cross-sectional area is better than large area modules.
- Cost of fabrication of semiconductor material should be less. Improved manufacturing techniques can help in this and can improve quality of the design of hybrid PV-TEG system.
- The total efficiency should justify the cost of the combined system, i.e. researchers should focus on economic analysis of hybrid PV- TEG system.

These systems have been validated to be a feasible unconventional power source at the locations where shelter heating is required and high reliability is an important factor.

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