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Solar photovoltaic/thermal-thermoelectric generator performance review

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Abstract. Solar photovoltaic (PV) cells are currently limited by the temperature factor that causes the drop of efficiency when the module temperature rises. Many approaches were made to solve the issue so that the performance of the solar cell is improved including the integration of thermoelectric generator (TEG) hybrid. The objective of these improvements is to increase the temperature coefficient that will enhance the efficiency of the solar cells. Some approach may produce other benefits like thermal energy or building integration other than producing electrical energy. Common PV panels only utilize 15-30% of the irradiation received while the rest of it are reflected away or turned into heat waste. In this paper, the relationship of PV heat waste and PV performance relationship is explored. Photovoltaic/thermal-thermoelectric generator (PV/T-TEG) hybrid layouts were compared based on its performances including overall efficiency to identify solutions for this type of application. PV efficiency and losses due to thermal limits will demonstrate the issue as temperature increases. Solar cell that is available in the current market is simulated for its temperature prediction and heat dissipation. This will determine the potential application for a TEG hybrid. Previous conducted experiments and simulations show a 0.14% to 5.2% increment in electrical efficiency. The prediction model will agree with this range of finding. The current advancement in solar PV/T-TEG is compiled and the future approach that can be taken to solve the temperature limits will be discussed.

1. Introduction

It is forecasted by the United Nations in its *World Population Prospects* that by the year 2050, the global human population will be increasing by 2.2 billion souls from today's figure and 68% of these populations will be accumulated in major and new cities [1,2]. This is alarming as our practice of managing the world resources is still a far cry from sustainable. It will be affecting three major needs of today's civilization – the food, water and energy nexus [3]. Processes involving food production and clean water supply requires huge amounts of energy anywhere along the line of agricultural, pasteurization, storage, desalination, etc [4]. As the requirement for food, water and energy and in a synergistic relationship, solving the energy factor can create a big impact in securing the future supply.

Moving towards this goal, a clear vision on securing energy supply by focusing on sustainable and renewable energy will be essential. A few scholars believe that a sustainable energy is one that is produced locally [5]. For example, a city of 50,000 people utilizes energy produced in their city sufficiently, with little to no waste and use the energy in smarter ways. Therefore, cities can look for the resources like solar, wind, hydro, geothermal, waves and biomass energy that are available in abundance locally.

Solar has a potential application for energy source in Malaysia. The country is located between 0.85° N to 7.27° N in the northern hemisphere. The yearly average amount of solar hours is consistently within 12 hours \pm 10 minutes [6]. However, long term rains, overcast and insolation records throughout the year reduces the monthly average daily solar irradiance, as estimated by Sopian, and Shavalipour to less than 17 MJ/m²/day [7,8]. This limits the efficiency of solar thermal and electrical systems. Both types of systems are available in small and industrial scales.



Malaysia is mainly focused on food processing and water heating as electrical systems are still expensive for local application [9]. The electrical system used in Malaysia mainly utilizes the photovoltaic panels. These panels are efficient under direct sunlight but suffer from infrared waves which increase its cell's temperature, thus reducing its efficiency [10].

Studies on PV/T solar collectors have been conducted in numerous amount but very few had implement the use of thermoelectric generators (TEG). The purpose of the TEG in a PV/T system is to take advantage of the heat losses from a PV panel and generate electricity and secondly to reduce the thermal losses from the collectors.

The geometric integration parameters like the type of absorber plate, thermal resistance, and TEG location are factors for the difference between the simulation and experimental works. The effects of design parameters, such as thermal conductivity between the PV cells, fin efficiency and their supporting structure, and lamination method, on both the electrical and thermal efficiencies of the PVT were essential to determine the overall performance. Furthermore, PVT can be prepared by using lower cost materials, such as pre-coated color steel with small reduction in efficiency.

There exist a few methods to improve the performance of solar harnessing technology. A new hybrid system that combines the best of both thermal and electrical harvesting system is finally on a rise both in study and application [11–20]. It is called Photovoltaic/Thermal (PV/T) which uses photovoltaic panels and combined with thermal extractor. It has massive benefits in utilizing the limited area, utilizing the light spectrum at a bigger band, increasing overall efficiency and operation life. The objective of this paper review is to identify the performance of PV under thermal limits and collect empirical results obtained by current studies in the performances of PV/T-TEGs hybrid. Also, the relationship of PV heat waste and PV performance relationship is explored.

2. PV Efficiency and Losses Due to Thermal Limits

Solar cell deficiency is inherent in all three current generations of solar PV cells due to a few limiting factors which will then determine the optimum design of a PV and PV/T module. On a single-junction solar cell, the limiting factors are identified from thermodynamic losses, Shockley-Queisser and other additional losses such as optical losses, solar cell collection losses and material doping. Some of these factors are controllable during fabrication such as the optical loss, solar cell collection loss and material doping but not as prominent.

2.1. Thermodynamic loss

Thermodynamic loss is the most common limit that easily affects the performance of a PV cell. A PV module is seen as a heat pump engine where the side that receives the solar irradiance acts as a heat reservoir and the back panel behind the sun acts as a cold reservoir. Therefore, the flow to the cold reservoir is the heat loss, because the thermodynamic definition of efficiency for this heat pump engine is the ratio of work generated from heat flowing in.

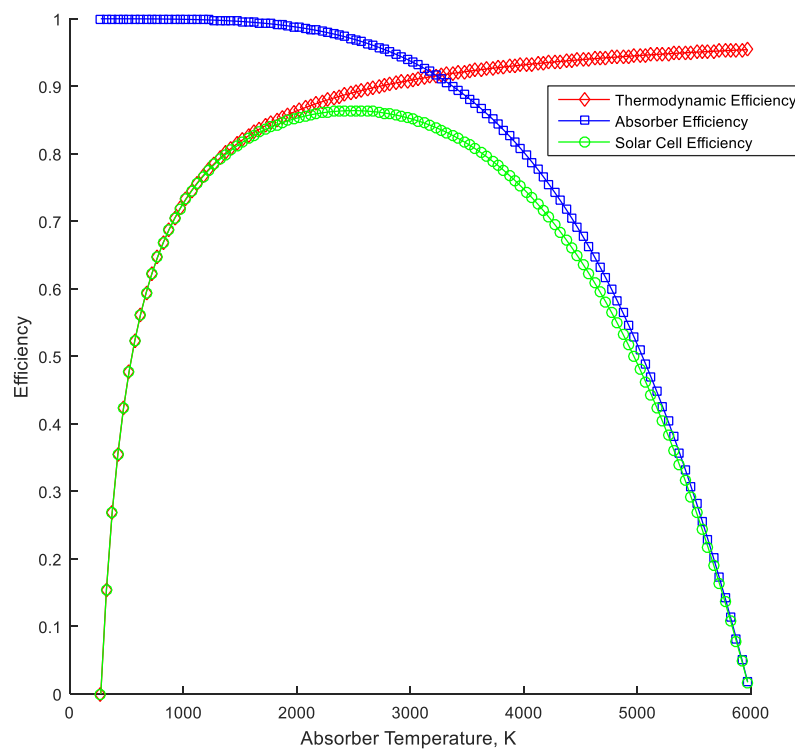
$$T_H - T_a = \left[\frac{G(T_{NOCT} - T_{a,NOCT})}{G_{NOCT}} \right] \left[1 - \frac{\eta_{PV}}{(\tau\alpha)} \right] \quad (1)$$

$$\eta_{SC} = \left(\frac{T_S^4 - T_A^4}{T_S^4} \right) \left(\frac{T_A - T_C}{T_A} \right) \quad (2)$$

With the increase in ambient temperature, T_a , of the atmosphere, the cell temperature, T_H , continues to increase at a constant solar irradiance, G . T_S refers the blackbody's surface temperature while T_A represents the absorber temperature. The results of theoretical efficiency at nominal operating cell temperature (NOCT) conditions, $T_{a,NOCT}$, W_{NOCT} and G_{NOCT} from Table 1 used by Duffie and Beckman, shown in Figure 1 [21].

Table 1. Parameters used in NOCT standard testing.

Parameter	Value
T_{NOCT}	$45 \pm 3^\circ\text{C}$
$T_{\text{a,NOCT}}$	20°C
W_{NOCT}	1m/s
G_{NOCT}	800W/m^2
$\tau\alpha$	0.9

**Figure 1.** Maximum theoretical efficiency that can be achieved by a solar cell under a certain temperature range.

Cell temperature and the sun's blackbody, indicates the maximum efficiency that can be reached by a solar cell is close 85% at 2,480K. However, this value is difficult to achieve unless an extremely efficient heat transfer module is used to cool down the cell temperature. Under normal conditions, the efficiency that can be achieved from a solar cell is between 15%-30%. Meanwhile, Figure 2 shows the relationship that is present when the ambient temperature dictates the theoretical cell temperature. The relative relationship is expected as the surface of the PV panel has a very high absorptivity ratio.

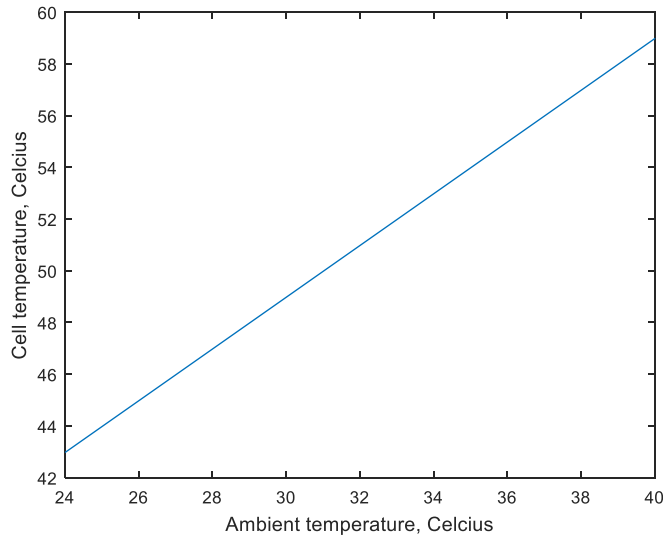


Figure 2. Dependency of cell temperature towards the increase of ambient temperature.

2.2. Cell performance degradation.

The performance of the solar cells will additionally degrade at high temperatures. To demonstrate this effect, the current-voltage, I-V and power-voltage, P-V curve in Figure 3a) and 3b) were simulated from an actual PV panel. The effect of temperature on panel is determined in the following equations:

$$I_{sc}(T_C) = \mu_{I,sc}(T_C - T_{NOCT}) + I_{sc}(T_{NOCT}) \quad (3)$$

$$V_{oc}(T_C) = \mu_{V,oc}(T_C - T_{NOCT}) + V_{oc}(T_{NOCT}) \quad (4)$$

$$I_o = I_L \left(\exp\left(\frac{V}{a}\right) - 1 \right)^{-1} \quad (5)$$

$$I = I_L - I_o \left(\exp\left(\frac{V}{a}\right) - 1 \right) \quad (6)$$

$$P = VI \quad (7)$$

$$\eta_{max} = \left(\frac{P_{max}}{AG_t} \right) \frac{100}{800} \quad (8)$$

The parameter I_{sc} and V_{oc} are the measurements of short-circuit current and open-circuit voltage, $\mu_{I,sc}$ and $\mu_{V,oc}$ represent the temperature coefficients, T_C denotes the cell temperature, T_{NOCT} refers to the temperature at NOCT, I_o is the value of dark saturation current, I_L indicates the light current; and I , V and P represents the current, voltage and power respectively. Parameter a is a physical constant where $a \equiv nkT_C N/q$ where n is usually 1.5, k denotes the Boltzmann's constant (1.381×10^{-23} J/K), N represents the number of cells in series, and q is the electronic charge 1.602×10^{-19} C (1 C = 1 A).

Figure 3a) and 3b) shows the performance I-V and P-V curve of a 200W rated solar panel with 72 cells, temperature coefficients of voltage and current are -0.33%/K and 0.03%/K respectively, T_{NOCT} at 25 °C, I_{sc} is 5.93A and V_{oc} is 45.2V. It is important to acquire manufacturer's specification to save time for simulation. Otherwise, experiment can be conducted to confirm the performance. V_{oc} and P decrease while I_{sc} increases as the temperature of the panel increases from 20 °C to 140 °C. It is significant to change the value of V_{oc} to see the effect of temperature on solar cell. The result shows

the maximum power voltage and maximum peak power decreases as cell temperature increases to 140 °C. Furthermore, Figure 3b) shows that, the module efficiency drops to 1.8% when the PV module temperature reaches 140 °C. Therefore, the general solution to increase the efficiency of the PV panel is to increase the cell temperature while instantaneously removing the heat thereby avoiding the degradation of cell efficiency. This condition is acquired through the method used in PV/T, which utilizes the heat in many forms [22-35].

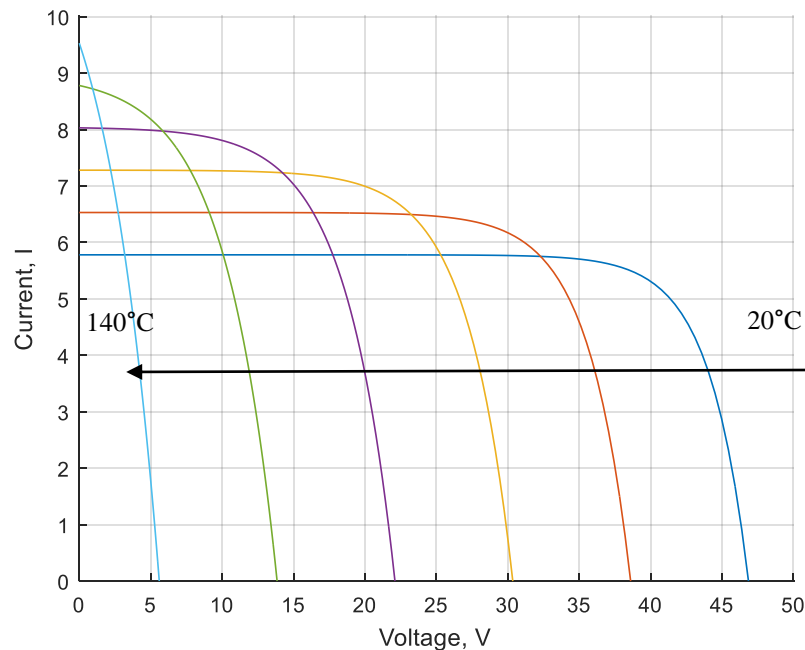


Figure 3a) I-V curve and

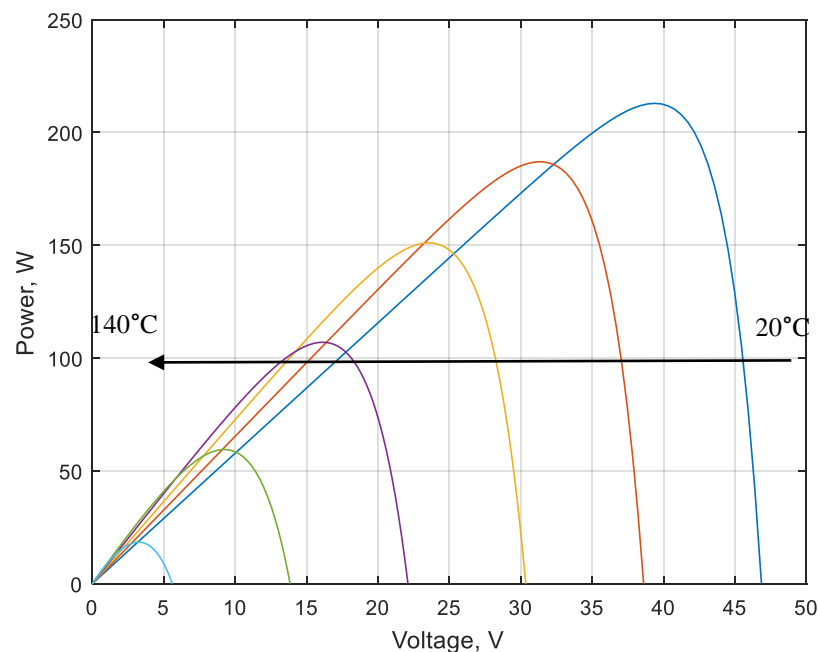


Figure 3b) P-V curves show the effects of temperature for a 200 W rated solar panel

3. Performances of PV/T-TEG solar collector hybrid

The studies in PV/T-TEG hybrid is getting more attention the past five years as new performing materials are more available to the public. These new materials are called thermoelectric generators (TEG) taking advantage of the waste heat produced by the solar energy that was not converted into electricity by the solar panel and turn it into auxiliary electrical energy. TEG has been used in other applications in medium to high thermal energy removals successfully [36–38]. These accomplishments have encouraged the study for low thermal energy systems in the likes of solar PV/T systems, where 40-60% of its efficiency comes from thermal energy. The potential application is it can increase and optimize the efficiency in the sub- and entire systems.

3.1 Improvements of solar PV/T-TEG technologies in the past

Table 2 shows a collection of PV/T-TEG hybrids technologies that had been researched in the past. Each of the studies uses different methods – includes simulations using analytical, numerical and software analysis and also a few experimental, with the final result focusing on observing the performance of each configurations.

The main component that must be used in a PV/T-TEG hybrid system is a PV cell or panel and a thermoelectric generator. The PV panel can consists of different materials, ranging from monocrystalline, polycrystalline, amorphous, multi-junction and thermos-photovoltaic. TEG meanwhile uses mainly two types that are common in the market, Bismuth Telluride, Bi_2Te_3 and lead telluride, PbTe . Additional components can consist of different mechanics and functions such as a solar irradiance concentrator, heat exchanger and thermal absorbers. Each of these can be used either to increase the amount of concentrated solar irradiation, heat removal from TEG to create its surface temperature difference, restrict certain spectrums of the solar light to be reflected, and cooling or heating purposes.

Table 2. A collection of recent research in the field of PV/T –TEG field and the efficiency achieved¹.

No.	Author	PV/T-TEG Layout	Cooling Application	Cooling Means	ΔT , K	Efficiency	Cost (\$/Wp)
1	[39]	PV-TE-HE	Heat Sink	Free convection	-	η_{PV} : 14.03%, η_{TE} : 3.2%, $Z=0.01/\text{K}$ at $1000\text{W}/\text{m}^2$	5.00
2	[40]	PV-TEG-HE	Heat Sink	Free convection	-	η : 4.1%, $ZT=4$	4.00
		CT-TEG-HE	Heat Sink	Free convection	-	η : 15.3% at 95 sun, $ZT=2$	4.00
		CT-PV-TEG-HE	Heat Sink	Free convection	-	η : 12.4% at 55 sun, $ZT=2$ η : 21% at 55 sun, $ZT=4$	4.00
		PV-CT-TEG-HE	Heat Sink	Free convection	-	$\eta_{\text{PV-TE}}$: 17% at 211 sun, $ZT=2.4$ $\eta_{\text{PV-TE}}$: 15.6% at 122 sun, $ZT=2.4$	4.00
3	[41]	VT-CT-SSA-FP-TE(HE)	Heat Sink	Free convection	-	η : 4% at $1000\text{W}/\text{m}^2$	0.05
4	[42]	CT-SS-((PV-HE)-(F TEM-HE))	Heat Sink	Free convection	468.5	$\eta_{\text{PV-TE}}$: 27.5% at 770 sun $\eta_{\text{PV-TE}}$: 26% at 550 sun	-
5	[43]	CT-PV-TEG-HE	Heat Sink	Free convection	-	η : 15% at $800\text{W}/\text{m}^2$ η : 11.5% at $5000\text{W}/\text{m}^2$	

¹ The abbreviations used in Table 2 are as follows. PV: photovoltaic cell; TE: thermoelectric; TEC: thermoelectric cooler; TEG: thermoelectric generator; TEM: thermoelectric module; HE: heat exchanger; VT: vacuum tube; CT: concentrator; FP: flat plate; SS: spectrum splitter; SSA: selective surface absorber; and G: glazing; I: Insulation

No.	Author	PV/T-TEG Layout	Cooling Application	Cooling Means	ΔT , K	Efficiency	Cost (\$/Wp)
6	[44]	G-PV-FP-TEG-HE	Water	Double Pass, Forced convection	50	η_{PV-TE} : 23% at 650W/m ²	4.00
7	[44]	I-PV-FP-TEG-HE	Air	Channeled, Forced convection	-	η : 29.7%	-
		I-PV-FP-TEG-HE	Water	Channeled, Forced convection	-	η : 28.4%	-
8	[46]	G-PV-TEG	Air	Free convection	-	η : 5.8%, η_{PV} : 4.3%, η_{TE} : 5.2% at 600W/m ²	-
9	[45]	G-EVA-PV-EVA-TPT-FP-HP-TEG-H	Heat Pipe, Heat sink	Free convection	65	η : 12.5% at 1000W/m ²	-
10	[46]	CT-SSA-HP-TEG-H	Heat Pipe, Heat sink	Free convection	25	η : 0.14% at 4 suns	-
11	[47]	CT-TEG-HP	Water, Heat Pipe	Vacuum pressure, Forced convection	37	$\eta_{thermal}$: 18.3% passive cooling, $\eta_{thermal}$: 33.2% active cooling	-
12	[48]	CT-PV-TEG-HE	Heat Sink	Free convection	40	η : 42% at 1000 sun	0.80

van Sark studied the feasibility of photovoltaic-thermoelectric hybrid modules due to the problems of operating PV cells under elevated temperature which causes conversion of efficiency drops as much as 25%. By simulating at two locations, Malaga and Utrecht, a system that consists of a PV cell, TEG and a Heat Sink in Fig xx, theoretically, could achieve 10.78% for PV efficiency and 3.2% for TEG efficiency in Malaga. A higher irradiance and ambient temperature results in more energy production. It also double the TE efficiency if the merit of $Z=0.01K^{-1}$ at 300K for this setup. However, the front and side covers heat flux and radiation losses are not taken into account during simulation. The author also assumes that the cold side of the TE will be the same as ambient temperature using natural convection. Meanwhile, the PV application can costs as much as twice than normal PV system based on the 2011 market prices at \$5.00/Wp.

Chávez-Urbiola in his paper studies four possible layouts for a solar hybrid systems with thermoelectric generators. A simulation was conducted to see the performance of each system at 1000W/m² solar irradiance. The TEG in this experiment is suitable for low heat application. The first layout which was using only PV cell, TEG and a Heat Sink was neglected due to lower heat flux in the system compared to the authors other layout refer Figure xx. The results shows that a linear dependence was achieved for TEG efficiency to temperature difference. A 4% efficiency at $\Delta T = 155^{\circ}C$ with 3W generated. Through his conclusion, there is a possibility to increase electricity production from a PVT system by flowing the heat flux from a PV cell and heat extraction in between a TEG or heat engine. The system design reaches its lowest cost at \$4/Wp. Through this work it is noted that a TEG with higher bad gaps can provide a more efficient system.

4. Conclusion

PV/T-TEG hybrid systems performance results has shown its potential to produce two forms of energy and improving the overall efficiency of the system by solving the thermodynamic limits. The operation life of PV panels or cells is also improved since the thermodynamic limits were reduced. The PV panel efficiency performance is increased based on the amount of thermal energy successfully removed from its surface.

Most of the analysis considered the situation of the environment to be constant, ambient temperature at 25 °C and studied in steady-state conditions. The temperature difference indicates the difference of temperatures experienced between the two surfaces of the TEG. This showed a promising result with the highest electrical efficiency to reach 42% at 1000× solar concentration. However, a practical result was at 14% for PV efficiency and 3% TEG efficiency, which amount to 17% electrical efficiency. Nevertheless, not many researches have been conducted in the field to actually prove the models.

These results open a multitude of applications with this hybrid system. Solar food drying has only been utilizing thermal energy can now be producing its own electricity efficiently with this system. Water heating can also benefit from this system by producing electricity or be self-sufficient by using independent source of energy to run its own pump. Building heating, cooling and ventilation can be improved by using the temperature difference between the PV/T-TEG system's surface temperature and the buildings air temperature.

Further studies can be made with the improvement of PV and TEG materials and technology in the future. Other studies could focus on improving the thermal management for the PV/T-TEG systems. The main concern today is material costs as most materials are not easily available and still costs \$4.00/Wp, which is considerably more expensive than traditional fossil fuel.

5. Acknowledgements

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