



# DEVELOPMENT OF HYBRID THERMOELECTRIC AND PHOTOVOLTAIC POWER GENERATION

Mohd Shawal Jadin, Nur Asyikin Setapa and Amir Izzani Mohamed

Sustainable Energy & Power Electronics Research, Faculty of Electrical & Electronic Engineering, Universiti Malaysia Pahang, Pekan, Pahang, Malaysia

E-Mail: [mohdshawal@ump.edu.my](mailto:mohdshawal@ump.edu.my)

## ABSTRACT

Hybrid photovoltaic and thermoelectric systems more effectively convert solar energy into electrical energy. Two sources of energy are used in this project. One of the energy is solar energy that converts radiant light to electrical energy. The other one is heat energy, which converts heat energy into electrical energy. Therefore, this project will utilize both of the solar radiation and heat from the sun as to generate more electricity. The aim of this project is to build a hybrid system that will increase the efficiency of the power generation system. In this research, the output power of the hybrid is equal to the sum of the maximum output power that produced separately from the individuals of the PV module and TE generator devices. The maximum output power that can be generated was up to 99.27 watts respectively. Overall, by using hybrid PV-TE generator system, the output that can be generated is better than the individual system.

**Keywords:** photovoltaic, thermoelectric, hybrid system, solar radiation.

## INTRODUCTION

8<sup>th</sup> Malaysia Plan (2001–2005) has targeted to generate 5% of the country's electricity from renewable energy sources by 2005. However, only 0.3% was achieved. This was further emphasized in the 9<sup>th</sup> Malaysia Plan where the efforts in the utilization of renewable energy resources and efficient use of energy were extensively promoted [1]. The actual harvesting of solar energy is still below their full potential. Therefore, by applying a hybrid system could help to increase the conversion efficiency.

This paper will explore the possibility of integrating the PV system with thermoelectric (TE) generator in order to increase the power generation. The two sources of energy which are solar and heats will be utilized to convert into electricity. PV directly converts into electricity from sunlight (solar radiation) while TE generates electricity when there is a different temperature occurs at the junction of two conductors according to the Seebeck effect. There is a huge potential of employing TE generator in which various wasted heat sources can be harvested to convert into electricity. One of advantage of TE generator is that it is free of maintenance and ease in operation just like a PV system.

This paper will deeply focus on the designing and modelling a hybrid TE and PV power generation system. The remainder of this paper is organized as follows: Section 2 discusses the basic theoretical studies of TE. The research methodology is given in Section 3. Then, result and discussion are given in Section 4 and finally concluding remark appears in Section 5.

## PV AND TE POWER GENERATOR

TE power generator is a device that will convert heat into electrical energy by applying the Seebeck effect. TE is one of the technologies that are to be deemed to recover and convert the industrial process of waste energy into more useful electrical energy. It will generate electric

current when there is a difference in temperature between its both sides. In one study, it shows the possibility to take benefit from the waste heats produced by manufacturing industries in Thailand by generating electrical energy harvested using TE generator system. Besides, the economic viability of the TE generator can also be increased when used for the waste heat recovery [2].

## PRINCIPLE OF TE

There are four main energy processes taking place in the TE pellets, which are thermal conduction, Joule heating, the Peltier cooling/heating effect, and the Seebeck effect. The phenomenon of thermal conduction is a Fourier process that is described by the thermal conductivity  $k_t$  of the material. For a TE with  $N$  thermocouples, the heat transfer of thermal conduction in a TE is described by

$$Q_{th} = -\Delta T k_t h \quad (1)$$

where  $k_t$  is the thermal conductivity of TE and  $\Delta T$  is a different temperature between hot and cold side. The total Joule heat dissipated in an  $N$ -couple TE is

$$Q_J = I^2 R \quad (2)$$

where  $R$  is its electrical resistance.  $I$  is the electric current that flow through TE. Irrespective of the temperature gradient, the Joule heat can be considered as equally divided between the two sides of the TE. The absorbed/emitted heat of an  $N$ -couple

$$Q_{PH/PC} = S I T_{H/C} \quad (3)$$

where  $S$  is the Seebeck coefficient and  $T_{H/C}$  is the temperature of the hot or cold side.

When a temperature gradient is imposed on a conductor under an open-circuit condition, the creation of an electrical potential difference between the hot and cool sides of the conductor is called the Seebeck effect. The



generated Seebeck voltage, called the electromotive force (EMF), in a TE is expressed as

$$U_S = S\Delta T \quad (4)$$

Applying the concept of energy equilibrium for steady-state analysis at both sides of the TE, the absorbed heat generated by the thermal load,  $Q_C$ , and the liberated heat removed by the heat sink  $Q_H$ , are respectively given by

$$Q_C = SIT_C - 0.5I^2R - \kappa_{th}\Delta T \quad (5)$$

$$Q_H = SIT_H + 0.5I^2R - \kappa_{th}\Delta T \quad (6)$$

where  $T_C$  is the cold side temperature and  $T_H$  is the hot side temperature. The TE's output voltage is then

$$V = U_S + IR \quad (7)$$

A good TE must combine a large Seebeck coefficient  $S$  with low electrical resistance  $R$  and low thermal conductivity  $\kappa_{th}$ . The figure-of-merit (FOM) parameter is then defined as

$$Z = \frac{S^2}{R\kappa_{th}} \quad (8)$$

where  $Z$  is the figure of merit. The regular parameters of TE involves the hot temperature,  $T_H$ , cold temperature,  $T_C$ , the power at the load matched,  $W_m$ , to the internal resistance ( $R_L = R$ ); the load voltage at the matched load,  $V_m (=V_R)$ ; and the maximum thermal efficiency,  $\eta_{th}^{max}$ . The electrical resistance  $R$  and the Seebeck coefficient  $S$  of a TE can be expressed as

$$R = R_L = \frac{V_m^2}{W_m} \quad (9)$$

$$S = \frac{2V_m}{\Delta T} \quad (10)$$

In fact, the efficiency of a TE is a function of the load. Assume that the load resistance is defined as  $R_L = mR$ , where  $m$  is the resistance ratio between the load and internal resistance. The current can be expressed as

$$I = \frac{S\Delta T}{[(1+m)R]} \quad (11)$$

The thermal efficiency of a TE generator is defined as the ratio of the electric power output to the thermal power input to the hot side, which can be expressed as

$$\eta_{th} = \frac{I^2 R_L}{Q_H} \quad (12)$$

The maximum current of TEG is the short-circuit current at zero load voltage,  $V_L=0$  which referred as

$$I_{shortcircuit} = 2I_m = \frac{2W_m}{V_m} \quad (13)$$

Based on Ohm's Law and the resulting Equation. (12) and (13), the voltage of TE generator can be obtained as

$$V = -R(I - I_{shortcircuit}) \quad (14)$$

## PV THEORY

PV is a part of the way, which can produce electrical energy by converting sunlight into direct current electricity by using semiconductor materials showing photovoltaic effect. The output of the PV module influences by the cell temperature, solar irradiance and the output voltage of the PV module [2]. The equivalent circuit of PV cell can be described as shown in Figure-1. The  $I_{ph}$  represent the photocurrent.  $I_o$  is the saturation current. While for  $R_{sh}$  and  $R_s$  represent the shunt and series resistance of the PV cell. Detail equation for PV cell is stated in [3].

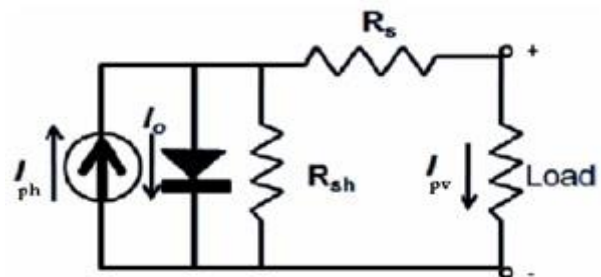


Figure-1. Condition the PV cell equivalent circuit [3].

The I-V and P-V output curve are the two important characteristics that should be considered in designing a PV system. These characteristics depends on the solar irradiance, temperature and output voltage from the PV module. The I-V curve is the output current-voltage characteristic of a PV cell or module. With this output curve, the maximum power can be obtained. The Figure-2 illustrates the I-V and P-V curves.

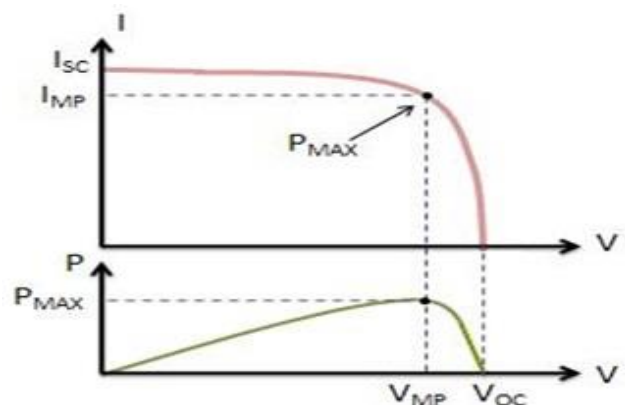


Figure-2. I-V and P-V output curve characteristics.



The current and voltage at this maximum power point are designated as maximum power voltage,  $V_{mp}$  and maximum power current,  $I_{mp}$ . By referring to the value of  $V_{oc}$  and  $I_{sc}$  of the PV module or cell, the value of  $V_{mp}$  and  $I_{mp}$  can be estimated. In the Standard Test condition (STC) this curve can be generated [4].

### HYBRID TE AND PV SYSTEM

The output power of a PV system depends on temperature and solar radiation [5][6]. It will increase as the solar radiation increased. However, when the temperature increases, it will reduce the output power of the PV module. In addition, the researchers also stated that the used of MPPT circuit is much recommended to be used in the hybrid system because it will stabilize the output power of the PV system [7]. Meanwhile, in one case study states that by using a dynamic analysis of hybrid TE and PV configuration using MATLAB the efficiency of the system will increase [8].

### RESEARCH METHODOLOGY

Prior to developing the hybrid system, simulation is required in order to get optimal system design. There is a need to test for different temperature for the TE generator modules. The objective of this test is to obtain the performance of TE generator at different temperatures between the hot and cold sides of TE module. The Matlab Simulink software is utilized in this project for the collecting and assessing the data. In the first step, the characteristic of the individual system of TE generator and PV system will be evaluated. Then, a complete system of the hybrid system will be simulated to study its performances. Finally, the hybrid system is developed. The performance of the system was tested with the real data. A comparison is made between simulation and real results.

### TE GENERATOR

Table-1 provides the specification of TE generator that was used in designing the hybrid system.

**Table-1.** Specifications of TE generator.

Brand Name	Thermonamic
Model Number	TEG200-24V
Heat source	543 K
Water temperature	300 K
Matched output power	200 W
Matched load output Voltage	24 VDC
Matched load output current	8.4 A
Open circuit voltage	48 VDC
Dimension Size	106 mm × 120 mm × 600 mm

The different temperature can be determined by using Equation. (15) and Equation. (16).

$$\Delta T = T_h - T_c \quad (15)$$

$$\Delta T = \frac{(T_h + T_c)}{2} \quad (16)$$

Based on  $T_h$  and  $T_c$ , the  $T_{ave}$  can be determined based on the value of  $V_m=24$  V,  $W_m=200$  watt and  $\Delta T=243$ K and using the Equation. (9) and (10). Thus, the electrical resistance,  $R$  and the Seebeck coefficient,  $S$  of a TE generator can be obtained. Through Equation. (11), the current value can be obtained with value  $m=1$ ,  $R=2.88$  and  $S=0.1975$ . The  $Q_H$  and  $k_{th}$  in  $W/m^2$  can be determined by

$$k_{th} = \frac{Q_L}{A\Delta T} \quad (17)$$

where  $Q_L$  is the amount of heat transfer through the material in J/S or Watt and  $A$  is the area of the body in  $m^2$ .  $\Delta T$  is the difference temperature between cold and hot side. When the value  $Q_H$  and  $k_{th}$  are obtained, the thermal efficiency can be determined by using

$$\eta_{th} = \frac{I^2 R_L}{Q_H} \quad (18)$$

The FOM can be defined by

$$Z = \frac{S^2}{Rk_{th}} \quad (19)$$

Given the FOM, the TE generator's thermal efficiency can be determined by

$$\eta_{th} = \frac{mZ\Delta T}{\{(1+m)^2 + Z[(m+0.5)T_h + 0.5 T_c]\}} \quad (20)$$

TE generator efficiency is the function to the ratio of  $m$ . So that, the maximal efficiency can be determined by using

$$\eta_{th}^{max} = \frac{(m_{opt} - 1) \left( \frac{\Delta T}{T_h} \right)}{\left( m_{opt} + \frac{T_h}{T_c} \right)} \quad (21)$$

Where,

$$m_{opt} = (1 + ZT_{ave})^2 \quad (22)$$

Therefore the maximal efficiency that gets from equation (21). Given the parameters of a commercial TE generator, the resistance ratio  $m$  can be obtained as

$$m_{opt} = \frac{(\Delta T + \eta_{th}^{max} T_c)}{(\Delta T - \eta_{th}^{max} T_h)} \quad (23)$$

After that, the FOM of the TEG can be found as



$$Z = \frac{(m_{opt} - 1)}{T_{ave}} \quad (24)$$

Then, the thermal conductivity of TEG can be determined

$$k_{th} = \frac{S^2}{RZ} \quad (25)$$

The efficiency at the matched load is expressed as

$$\eta_{th,m} = \frac{Z \Delta T}{[4 + Z(1.5T_h + 0.5T_c)]} \quad (26)$$

The FOM of the TEG is then calculated by

$$Z = \frac{4 \eta_{TEG}^{max}}{[\Delta T - \eta_{TEG}^{max}(1.5T_h + 0.5 \times T_c)]} \quad (27)$$

## PV SYSTEM

In general, PV module will convert energy from the sun into DC current. The DC current will flow through a power conditioner to supply load through an inverter. The daily output or energy produced by a PV module is given by

$$EPV = A_{PV} \times E_{sun} \times \eta_{PV} \times \eta_{inv} \times \eta_{wire} \quad (28)$$

where  $A_{pv}$  is the area of the PV module,  $E_{sun}$  is daily solar irradiation.  $\eta_{pv}$  is the efficiencies of PV module,  $\eta_{inv}$  is the efficiencies of inverter and  $\eta_{wire}$  is the conductor efficiency. The difference between the energy at the front end of a PV system,  $E_{pv}$ , and at the load side is given by

$$Energy\ difference = \sum_{k=1}^{366} (E_{PV} - E_L), \quad (29)$$

where  $E_L$  is the load energy demand.

The energy difference may be either positive ( $E_{pv} > E_L$ ) or negative ( $E_{pv} < E_L$ ). If the energy difference is positive, it means that there is an excess of energy, and if it is negative then there will be an energy deficit. The excess energy is stored in batteries in order to be used in case of an energy deficit. Meanwhile, the energy deficit can be defined as the disability of the PV array to provide power to the load at a specific time. For optimizing SAPV, the following parameters are defined for sizing a PV array and battery storage, respectively.

$$c_v = \left( \frac{c_{pv}}{c_L} \right) \text{ and } c_s = \left( \frac{c_B}{c_L} \right) \quad (30)$$

where  $C_B$  and  $C_{PV}$  are the battery capacity and PV array capacity at the specific load, respectively.  $C_L$  is the load demand.

Solar radiation and temperature that were taken from the weather station will be used to calculate the generated current and the generated power. With the using

formula below, the generated current and generated power can be obtained. These outputs will be compared with the output that generated from the MATLAB Simulation. Solar radiation and temperature will become the input to generate current and power output. The generated current under standard condition ( $25^\circ\text{C}$ ) is given as

$$I(T_1) = G \times \frac{I_{sc}(T_1)}{G_{nm}} \quad (31)$$

where  $T_1$  is the standard temperature under test condition ( $25^\circ\text{C}$ ),  $G$  is solar irradiation in  $\text{W/m}^2$ ,  $I_{sc}$  is the nominal current of the module in A and  $G_{nm}$  is nominal solar irradiation ( $1000 \text{ W/m}^2$ ). Then, using equation (32), the generated current at a given temperature,  $I_L$  can be computed.

$$I_L = I(T_1) \times (1 + K(T - T_1)) \quad (32)$$

where  $T$  is the temperature of the area under study and  $K$  is the temperature coefficient of the module at  $I_{sc}$ . The generated power can be calculated by using the formula below

$$P = I_L \times V \quad (33)$$

$V$  is the PV module open circuit voltage.

MPPT is a technique that is used by solar charge controller to get the maximum possible power from a PV system [9]. MPPT is used for prediction of the maximum power point occurrence by using perturb and observation. An algorithm will find maximum by reading voltage and current. From that, it will increase the fill factor [10]. Maximum efficiency is defined by the ratio between the maximum power and the incident light power. While, the fill factor is the ratio of the maximum power that can be given to the load and the product of  $V_{oc}$  and  $I_{sc}$ . The maximum efficiency and fill factor are defined by formula as shown below.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{max} \times I_{max}}{A \times G_a} \quad (34)$$

where  $G_a$  is the ambient irradiation and  $A$  is cell area.

$$FF = \frac{P_{max}}{V_{oc} \times I_{sc}} = \frac{V_{max} \times I_{max}}{V_{oc} \times I_{sc}} \quad (35)$$

where  $V_{oc}$  is the open circuit voltage and  $I_{sc}$  is the short circuit current, respectively.

## SYSTEM MODELING AND HARDWARE DEVELOPMENT

The hybrid system combines with the solar PV system with the reliability and heating capability of a TE generator. Figure-3 shows the block diagram of a hybrid system between TE and PV power generation. The energy deficit is identified as the disability of the TE and PV module to provide power to the load at a specific time.





The Figure-4 and Figure-5 show the complete model of the hybrid.

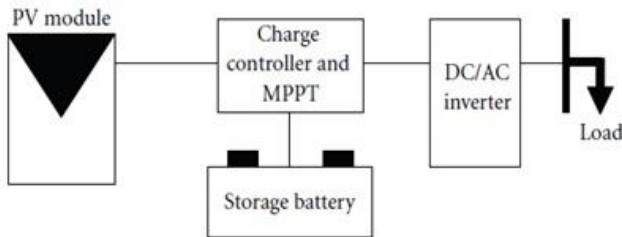


Figure-3. The PV block diagram.

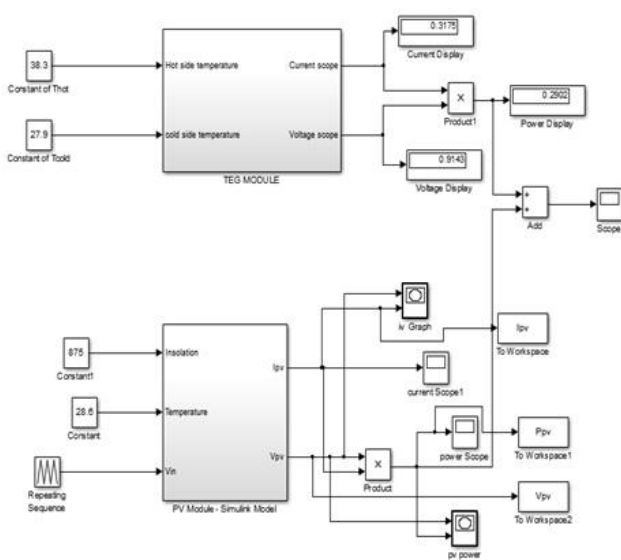


Figure-4. Hybrid system in MATLAB.



Figure-5. TEG development.

## RESULTS AND ANALYSIS

To test the system, hot water was boiled by using a water heater. In the experiment, the result was recorded every three minutes. The initial reading for the hot and cold temperature is at 27.7 °C and 28.8 °C, respectively. The TE system can generate power between 0.0036 to 19.22 watts for the temperature range between -1.3 °C to

42.4 °C. The result shows that the power generated from TE generator increases as the temperature increase. In simulation, the power that can be generated is between 0.0042 to 4.82 watts. As illustrated in Figure-6, the output voltage that can be reached was 6.40 volts. The output current that can be generated ranges from 1.49 A to 3.25 A. While from simulation, it can generate from 0.79 A to 1.65 A. The output current that was taken from measurement is higher than from simulation.

For analysing the performance of the PV system, a model was created based on the real PV module specifications. SW80 mono/R5E Solar World PV module was used to design the system. Detailed PV module specifications are given in Table-2. The location of the experiment was carried out in the Universiti Malaysia Pahang. The experiment was run under different temperature and solar radiation as given in Table-3. When the solar radiation increases, the current and voltage also increase. The Figure-7 shows the power generated that was taken from the 8.00 am to 5.00 pm. It shows the measured power from the PV module and the power from MATLAB simulation.

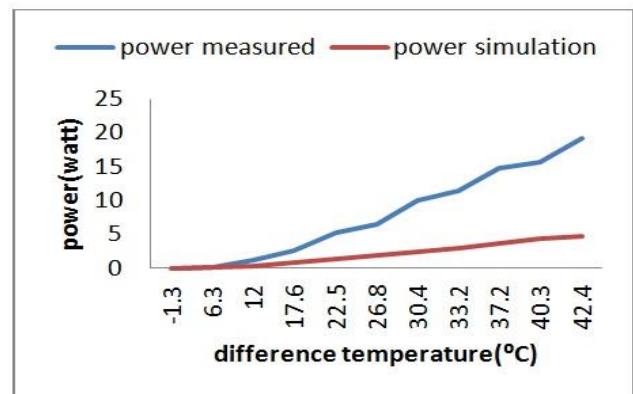


Figure-6. The output power of TE generator vs different temperature.

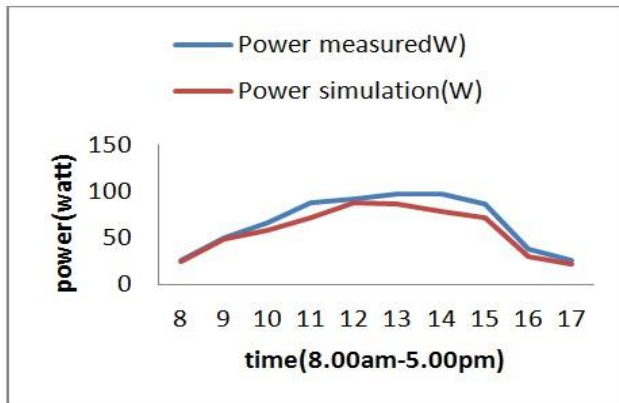
Table-2. Specifications of SolarWorld PV module SW80 mono/R5E.

$P_{max}$	80 Wp
$V_{mpp}$	17.5 V
$I_{mpp}$	4.6A
$V_{oc}$	21.9V
$I_{sc}$	5.00 A
NOCT	46 °C
Thermal coefficient $I_{sc}$	0.036 %/K
Thermal coefficient $V_{oc}$	-0.33 %/K
Rated power	80 Wp +/- 5 %

The power that generated show in Figure-7 below is slowly increased from 8.00 am to 1.00 pm with the total



generated power between 25.72 to 97.94 watts. Then, from 2.00 pm to 5.00 pm, it slowly dropped due to the decrease of the solar irradiance and temperature. Based on the simulation result, the output power is almost the same with the actual measured values. The power starts to increase from 25 to 88 watt and drop from 86 to 22 watts. The graph shows that the power measured is higher than simulation.

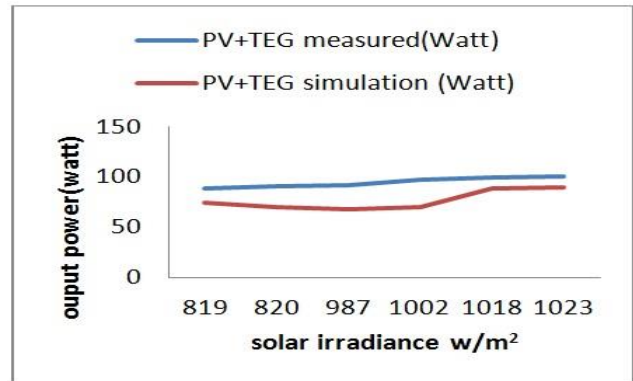


**Figure-7.** The power vs time of the PV module measured and simulation.

**Table-3.** Temperature and solar irradiance.

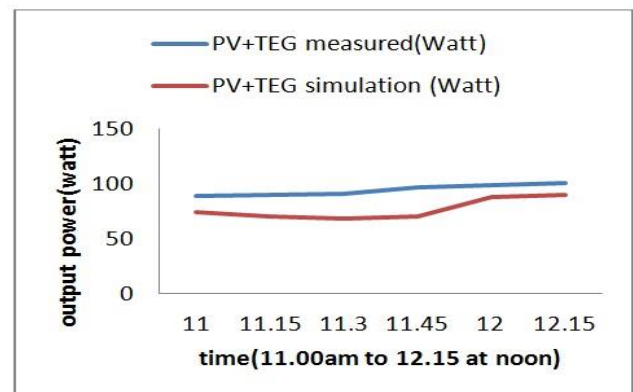
Time (hour)	Temperature (°C)	Solar irradiance (w/m <sup>2</sup> )
8.00	25.6	294
9.00	25.8	587
10.00	27.4	663
11.00	28.0	819
12.00	28.6	1018
13.00	28.5	993
14.00	28.3	896
15.00	27.8	816
16.00	27.8	376
17.00	27.6	285

The experiment between the PV module and TEG was conducted. During the experiment, the solar irradiance range between 819 w/m<sup>2</sup> to 1023 w/m<sup>2</sup>. While for the ambient temperature was between 28 °C to 28.6 °C. The reading of parameters were recorded every 15 minutes. As the hot-side temperature increase, the cold-side temperature also increases. Figure-8 shows the relationship between the output power of PV-TEG versus solar irradiance. It compares between measured value and simulated value. The measured output power is higher result compared to simulation.

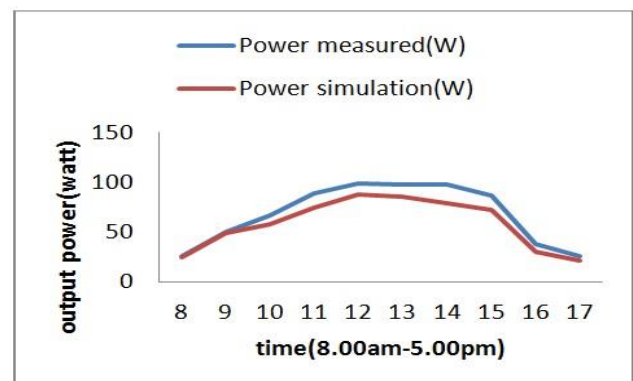


**Figure-8.** Hybrid power output vs. solar irradiance.

Theoretically, if the solar irradiance increase, the output will also increase. While in the Figure-9 below shows the hybrid output power versus time. This is due to the increase of temperature difference between the hot side and cold side. In this case, it is also shown that the measured output power is higher than the simulation value. Figure-10 shows the power generated by the measured and simulated value of the hybrid system. The hybrid output power measured is higher simulation value. Overall, by using a hybrid PV-TE generator system, the output that can be generated is higher compared with output power of the individual experiment.



**Figure-9.** Hybrid output power vs time.



**Figure-10.** The output power of hybrid TE-PV system vs time.



## CONCLUSION AND RECOMMENDATION

Based on the result and analysis of the development of the hybrid system between the PV and TE power generation, it showed that the system can produced a better power generated. It was stated that with the increasing in the difference temperature between the hot side and the cold side of the TE generator system, the output would increase. However, during the experiment, the voltage that can be generated is below than 10 volts. The highest value that can be generated from the individuals TEG experiment is about 6.40 volts only. The boiler that has been used can heat up the water up to 100 °C. However, TE may withstand up to 250 °C. Theoretically, the voltage should increase as the hot temperature increased and the temperature differences between the hot and cold sides must be as far as possible. To overcome this problem, the best liquid to replace water is oil that can keep a higher temperature. Another thing to consider is the flow rate of both cold and hot liquids. A study is required in order to optimize the flow rates. Overall, the proposed hybrid system could produce more power than the independent system.

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