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Development of Steg with Concentrating System

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ABSTRACT

Solar cells, also known as photovoltaic cells, convert light energy into electrical energy through the photovoltaic effect. Integrating a thermoelectric generator into a photovoltaic system enhances power output and efficiency by utilizing waste heat. Concentrators are employed to further improve solar panel efficiency. This study aims to develop a solar thermoelectric generator (STEG) with a concentrating system that includes a heat sink cooling system, thermoelectric generator, and concentrator. Three conditions will be tested to observe the power output of each solar module: PV standalone, STEG with a heat sink, and STEG with a heat sink and concentrator. The efficiency appears to improve from 9.21% for PV standalone to 10.11% for STEG with a heat sink and 10.23% for STEG with a concentrating system. The results of these studies aim to establish a benchmark for enhancing the efficiency of future STEG systems.

1. Introduction

Producing new energy from other sources is more efficient since fossil fuels are unreliable and renewable. Meanwhile, renewable energy is derived from natural sources that are replenished faster than consumed [1]. The amount of energy Earth receives from the sun is almost 1.8×10^{11} MW, which is one thousand times higher than the overall energy consumption of all energy sources [2]. The photovoltaic panel is the most widely adopted technology for directly converting solar radiation into electricity [3]. Nevertheless, conventional photovoltaic (PV) technology typically achieves an overall efficiency of approximately 17–18% in converting solar energy into electricity [4,5]. There has been a trend towards combining photovoltaic panels with thermoelectric generators (TEGs) to enhance solar energy utilization efficiency [6-9]. TEGs harness temperature differences on both sides to generate electricity, with voltage increasing as the temperature rises. TEG has the potential to

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convert solar energy at greater than 15% efficiency, and it is an intriguing way to generate renewable energy directly from waste heat. However, their efficiencies are limited due to their thermal and electrical properties being dependent on each other [10].

External components for regulating and dissipating heat have been investigated to minimize degradation related to the thermal tolerance of photovoltaic (PV) systems. Several cooling methods for PV systems have been explored [11]. For instance, natural wind cooling, which impacts below-average heat regulation, has been examined as an example. When a polycrystalline photovoltaic panel integrated with a TEG was used, it produced 10.81W of power. A photovoltaic panel without a TEG produced a power output of 8.78W. Adding a thermoelectric generator to the photovoltaic panel also increases the efficiency by 2.4% [12].

However, these PV modules undergo testing for power enhancement using heatsinks featuring active and passive cooling systems. The primary purpose of employing a heatsink is to efficiently dissipate heat from device components, enhancing performance and prolonging their lifespan [13]. Heatsinks typically consist of a thermal conductor that transfers heat from the heat source to fins or pins, providing a large surface area for heat dissipation [14]. Cooling systems compensate for the efficiency reduction caused by surface temperature increases. This passive cooling system does not consume electrical energy. Using passive heatsinks instead of active ones aims to minimize noise and eliminate the risk of overheating due to fan malfunctions. Integrating heatsinks into solar cells offers advantages such as ease of manufacturing, installation, and flexibility in PV module placement. Consequently, incorporating heatsinks can reduce working temperatures by up to 4.2% and increase output power by up to 5.5% [15].

A solar collector utilizes reflective surfaces to concentrate sunlight onto a limited area, where it is absorbed and transformed into heat, subsequently utilized to generate electricity. Solar concentrators are designed to collect and direct solar radiation towards a singular focal point [16]. As a result, various types of concentrators produce different temperature ranges. By concentrating a substantial amount of sunlight onto a smaller surface, solar concentrators can markedly enhance solar energy conversion efficiency [17].

The Thermoelectric Generator (TEG) plays a crucial role in converting excess heat into electricity. Subsequently, the temperature is cooled down concurrently with a heat sink and DC fan. Moreover, aluminium is employed to enhance sunlight concentration on the PV panel, thus optimizing power output. To achieve these objectives, a low-power PV panel integrated with a TEG, heat sink, and DC fan mounted on its backside has been tested and monitored within this framework. As a result, the research will focus on developing a methodology to assess the impact of concentrators on solar panel performance to achieve higher efficiency in power output.

2. Literature Review

2.1 The Efficiency of Solar Panel

The quantity of sunlight establishes the efficiency of the solar panel reflected onto its surface and converted into either electrical or thermal energy. Previously, solar panels typically had an average efficiency of approximately 15%. However, due to the advancements in photovoltaic technology, the current efficiency range of solar panels has increased to 18 and 30% [18].

For example, irradiance is the energy that strikes a unit horizontal area per unit wavelength interval per unit of time. It usually varies due to the weather, seasonal changes, geographical location, time of the day, and the sun’s position in the sky. According to the sun’s altitude changes, the sun’s location changes throughout the day [19]. Cloudy conditions are primarily responsible for variable irradiance value, as reported in Figure 1.

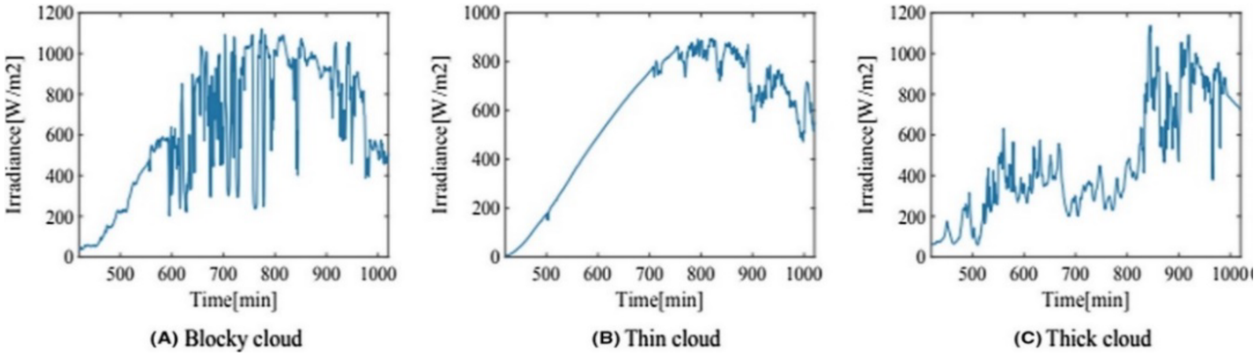


Fig. 1. Irradiance value changes with different cloudy condition [19]

Several things can affect a solar panel's efficiency, such as the type of solar panel, the inverter efficiency, and thermal cycling. Therefore, the performance or output of solar modules is heavily influenced by a few factors, such as irradiance, module temperature, shading, module mismatch, dirt, cable sizing, and aging [20].

Other than that, the fill factor is essentially a measure of the quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power that would be output at both the open circuit voltage and short circuit current together [21]. Fill factor (FF) is also an important measurement that can be used to evaluate the efficiency of solar cells. It will give a measurement that can be used to assess the performance of solar cells. The solar cell with a higher fill factor is more efficient and, therefore, more desirable [22]. The following equation is used to compute the fill factor:

$$FF = \frac{P_{\mathrm{mp}}}{V_{\mathrm{oc}}.I_{\mathrm{sc}}} \tag{1}$$

$$= \frac{P_{\mathrm{mp}}.I_{\mathrm{mp}}}{V_{\mathrm{oc}}.I_{\mathrm{sc}}} \tag{2}$$

where P_{mp} is the maximum power output, I_{sc} is the short circuit current and V_{oc} is the open circuit voltage. Fill factor is often referred to as a representation of the squareness of the IV curve. There is one way to determine the P_{mp} is as the maximum rectangular area that can fit inside the IV curve of solar cell as shown in Figure 2.

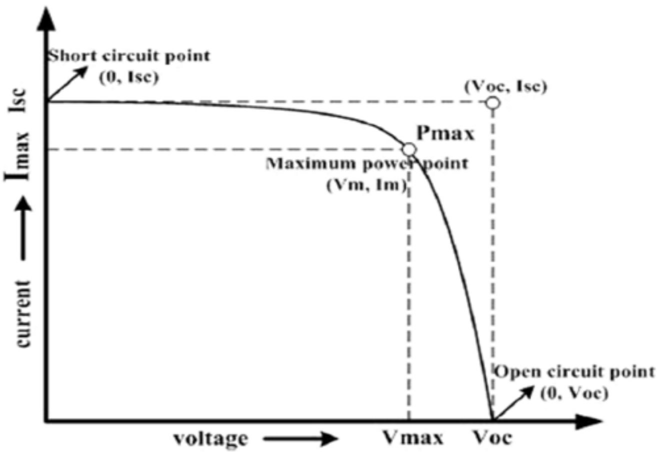


Fig. 2. Graph of Iv curve of solar cell [26]

Meanwhile, efficiency is the commonly used parameter to compare the performance of one cell to another. Efficiency is the ratio of energy output from the solar cell to input energy from the sun [23]. Hence, the ratio between the maximal generated power and the irradiance times area was used to compute the efficiency conversion:

$$\eta = \frac{P_{\max}}{G\chi A} \quad (3)$$

2.2 Summary of Related Study

Based on the journal and research studies in Table 1, some components are used similarly in each project. The researcher develops the system using a heat sink cooling system, optical concentrators, and a thermoelectric generator. This proposed project will consist of a combination of TEGs, a heat sink cooling system, and a concentrator, which will be employed together. This will help to achieve the desired output of solar modules.

Table 1
Summary of related study

No.	Authors	Title	Summary
1	Taleb M Maslamani, Abdu Idris Omar, Majid M. [24]	Development of solar Thermoelectric generator	A simple system deployed on rooftops can work in harsh environments, quiet in operation, and be capable of virtually endless shelf life.
2	Hasan T Hashim, Farhan Lafta Rashid, Mohammad Jawad Kadham *et al.,* [25]	Concentration solar Thermoelectric generator	Combining concentrating systems with the TEG system could increase the amount of electrical power generation from TEG and thermal power.
3	Sunarno A. Rakin, S. Suherman, S. *et al.*, [26]	A passive cooling system for increasing the efficiency of solar panel output	The passive cooling system does not consume electrical energy. It is applied by using a heat sink or a bottle of water that is absorbed by using cotton, another method is by keeping the bottom part of the solar panel in the water. Once it is installed, no additional water or energy is required, it also saves energy and space.
4	M. L. Olsen *et al.,* [27]	A high-temperature, high-efficiency solar Thermoelectric generator prototype	This STEG prototype design includes a thermally insulating cavity allowing concentrated sunlight to enter through an aperture but further limiting radiative losses.
5	Kenneth McEnaney, Daniel Kraemer *et al.,* [28]	Modeling of concentrating Solar thermoelectric generator	The optimization of cascaded and segmented TEGs will theoretically increase efficiency by 10%.

3. Methodology
3.1 Block Diagram

This is an overview of the workflow and process of the study, as shown in Figure 3. STEG will be developing a thermoelectric generator along with a heat sink and DC fan to minimize the temperature of the PV module and optimize the production of solar power output with the concentrator.

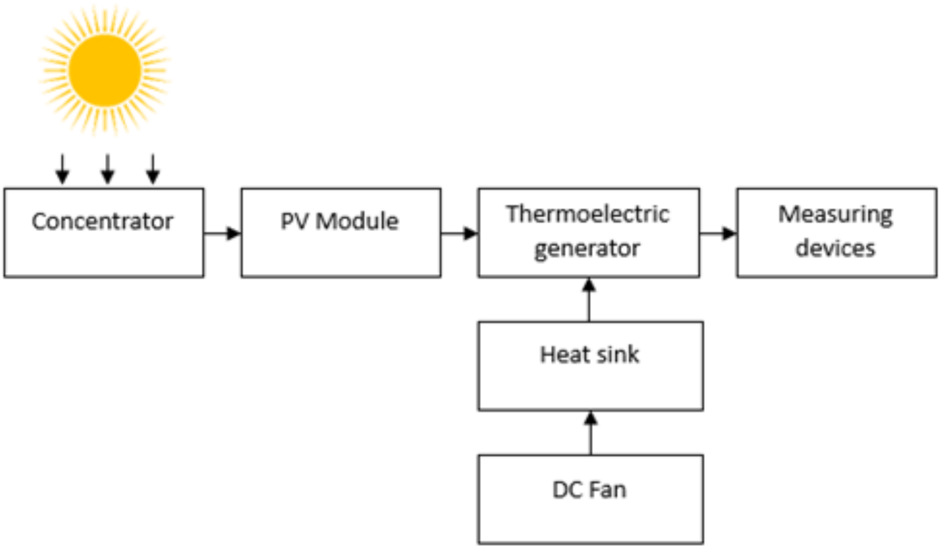


Fig. 3. Block diagram of Steg with concentrating system

3.2 Flowchart

This project will commence with the planning of developing a Solar Thermoelectric Generator (STEG) alongside a concentrating system, as illustrated in the flowchart shown in Figure 4. It will involve three types of testing: PV standalone without any cooling system, STEG with aluminium heat sink, and an additional test STEG with incorporating an aluminium concentrator into the system. The thermoelectric generator (TEG), heat sink, and DC fan will be mounted to the backside of the solar panel. The solar concentrator will be the primary focus for assessing the output performance of this solar concentrating system. Subsequently, the concentrator will harness a significant area of sunlight, redirecting it towards a specific spot by bending and focusing the light rays. The solar panel output results will be monitored periodically. The study will conclude with an efficiency comparison among the conducted tests.

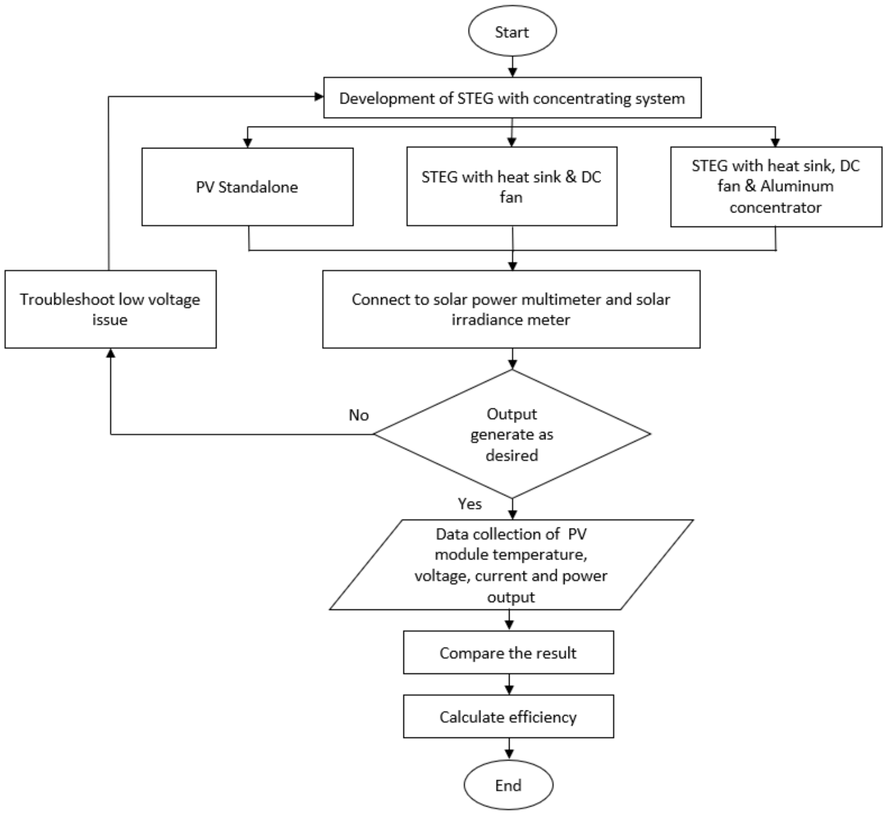
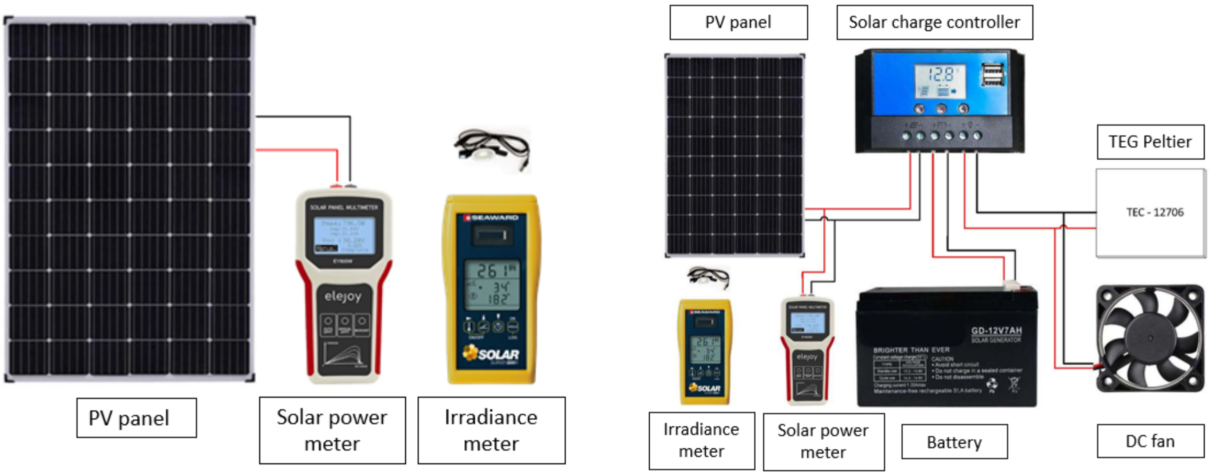


Fig. 4. Flowchart of the system

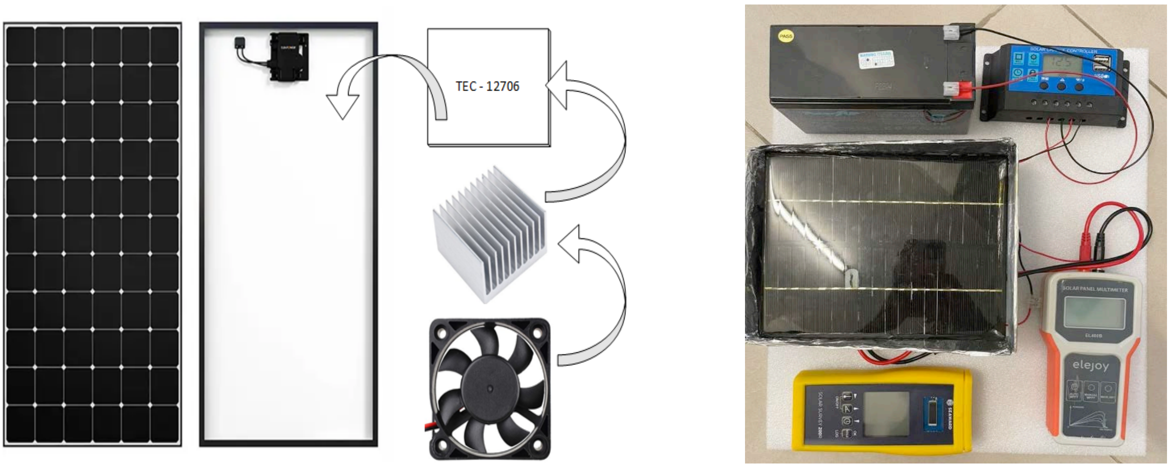
3.3 Hardware Development

This study utilized 6W monocrystalline PV panels and involved several components, including the Peltier module, DC fan, charge controller, and battery. For measurement purposes, a solar power meter and irradiance meter were employed. The PV panels were installed in three different configurations the first setup, depicted in Figure 5(a), consisted of a standalone PV system with a solar power meter and irradiance meter. Next, the second setup, illustrated in Figure 5(b), featured a Peltier module, heat sink, and DC fan mounted on the back to serve as a cooling system, as depicted in Figure 6. Lastly, the third setup involved the addition of aluminium as a concentrator, as depicted in Figure 6(a). The heat sink, 100 x 100 x 18mm, was fabricated from aluminium. Temperature and irradiance measurements were collected using the same data logger device. As shown in Figure 5(a), the irradiance meter's probe collected panel and ambient temperature data. A solar power multimeter measured current, voltage, and power output. The efficiency of the solar panel was assessed through this experimental setup. The panels were positioned on the ground in an outdoor location at Kolej Kediaman Kampus Pagoh, UTHM as in Figure 6(b). Experimental measurements and data collection were conducted between 9:00 AM to 4:30 PM Malaysia time.



(a) (b)

Fig. 5. (a) PV standalone system (b) PV with STEG system



(a) (b)

Fig. 6. (a) Position of Peltier, heat sink, and DC fan at the panel's backside (b) PV with STEG system and concentrating system

4. Results

4.1 Data Analysis for PV Standalone

In this test, the solar panels are employed and connected in series with the measuring devices without using other components such as the TEGs or heat sink. The output results are shown in Table 2, including irradiance, ambient temperature, the temperature for the PV module, and voltage open circuit (V_{OC}). In Table 2, it is evident that the irradiance readings fluctuate over time. The data indicate that the lowest irradiance was recorded at 9:00 AM, measuring 492W/m^2, while the highest irradiance occurred at 2:30 PM, reaching 842W/m^2. The module temperature demonstrates a general upward trend until 2:30 PM, followed by a gradual decline towards the evening. This trend is influenced by the exposure of the PV panel to sunlight, which could potentially impact its efficiency.

Table 2
Output for PV standalone

Time	Irradiance (W/m^2)	Ambient Temp (°C)	Module Temp (°C)	V_{mp} (V)	I_{mp} (A)	P_{max} (W)	V_{oc} (V)
9:00 AM	492	38.4	50	17.67	0.15	2.65	2.65
9:30 AM	575	34.2	50	18.07	0.15	2.71	2.64
10:00 AM	602	40.5	50	17.75	0.16	2.84	2.66
10:30 AM	603	42.2	51	18.13	0.16	2.9	2.66
11:00 AM	684	42.3	44	18.79	0.14	2.63	2.68
11:30 AM	709	43.2	50	18.00	0.11	1.98	2.66
12:00 PM	807	42.1	46	19.67	0.09	1.77	2.64
12:30 PM	821	41.7	47	19.78	0.09	1.78	2.64
1:00 PM	789	37.5	57	18.18	0.17	3.09	2.62
1:30 PM	805	37.7	55	18.41	0.17	3.13	2.62
2:00 PM	829	37.4	56	18.00	0.16	2.88	2.62
2:30 PM	842	37.5	57	18.19	0.16	2.91	2.61
3:00 PM	807	36	56	18.75	0.16	3.00	2.6
3:30 PM	821	36.2	51	17.88	0.16	2.86	2.62
4:00 PM	722	34.8	51	17.06	0.17	2.9	2.63
4:30 PM	729	34.8	50	17.67	0.15	2.65	2.65

4.2 Data Analysis for the Performance of the STEG System with a Heat Sink & DC Fan

To reduce the temperature of the solar panel, the heatsink and DC fan were installed with the TEG module. The dimensions of the heatsink are 100 x 100 x 80 mm, smaller than the solar panel, to ensure it fits the size. The results in Table 3, the output data of the PV panel equipped with a STEG system, heat sink, and DC fan, is presented and shows that the solar panel installed with the heatsink has a significant temperature drop than the solar without a cooling system.

Table 3
Output of PV panel with STEG system with a heat sink & DC fan

Time	Irradiance (W/m^2)	Ambient Temp (°C)	Module Temp (°C)	V_{mp} (V)	I_{mp} (A)	P_{max} (W)	V_{oc} (V)
9:00 AM	645	40.1	41	18.64	0.11	2.05	2.82
9:30 AM	668	40	42	18.36	0.14	2.57	2.85
10:00 AM	757	37.9	42	18.07	0.15	2.71	2.82
10:30 AM	792	38.3	43	17.31	0.16	2.77	2.83
11:00 AM	807	39.3	44	17.53	0.17	2.98	2.83
11:30 AM	842	41.5	46	17.59	0.17	2.99	2.83
12:00 PM	855	36.3	44	18.75	0.16	3.00	2.83
12:30 PM	857	38.2	41	18.29	0.17	3.11	2.89
1:00 PM	866	34.2	47	17.74	0.19	3.37	2.84
1:30 PM	855	34.9	46	17.20	0.2	3.44	2.83
2:00 PM	865	43	46	18.29	0.17	3.11	2.63
2:30 PM	816	43.6	44	17.88	0.17	3.04	2.84
3:00 PM	793	36.3	43	17.58	0.19	3.34	2.83
3:30 PM	720	38.2	44	18.29	0.17	3.11	2.89
4:00 PM	732	40	45	18.64	0.11	2.05	2.82
4:30 PM	705	40	45	18.36	0.14	2.57	2.85

In this case, it can be demonstrated that the presence of a heatsink has a significant impact, as the temperature was lower than the standalone solar panel. The module temperature for the PV standalone test was measured on the solar panel without a heatsink and DC fan. In contrast, the module temperature for the second test was measured on the solar panel along with TEG, heatsink, and DC fan. The values of the module temperature from Table 2 and Table 3 show the difference between the panel without the cooling system, which consistently shows higher temperatures throughout the day, and the panel with the cooling system, which exhibits lower temperatures. For example, at 11:30 AM, Table 3 indicates a temperature of 50°C, whereas Table 4 indicates a lower temperature of 46°C.

4.3 Data Analysis for the Performance of the STEG System with a Heat Sink, DC Fan Aluminium Concentrator

Solar panel with a STEG system and concentrator consists of a TEG module, heatsink, DC fan, and aluminium reflector. An observation was made of the changes in temperature level affecting the voltage output. Hence, the graph is plotted as shown below. Theoretically, the higher temperature levels will elevate the value of voltage. Table 4 shows the results of solar panels with STEG and concentrating system. Table 4 presents the results of PV panels installed with the heatsink and concentrating system. As previously mentioned, the heatsink plays a crucial role in lowering the temperature of solar modules to enhance power output. The temperature improvement is evident compared to the solar panel without a heatsink. This improvement is attributed to the heatsink attached to the backside of the solar panel, which absorbs heat and releases it to the surroundings through heat dissipation.

Table 4
Output of PV panel with STEG system and concentrating system

Time	Irradiance (W/m^2)	Ambient Temp (°C)	Module Temp (°C)	V_{mp} (V)	I_{mp} (A)	P_{max} (W)	V_{oc} (V)
9:00 AM	718	34.2	43	17.22	0.18	3.1	3.02
9:30 AM	722	34.9	44	17.39	0.18	3.13	3.03
10:00 AM	779	40	43	17.28	0.18	3.11	3.03
10:30 AM	815	39.8	42	18.05	0.19	3.43	3.05
11:00 AM	830	40.5	44	18.00	0.18	3.24	3.04
11:30 AM	878	42.2	45	17.42	0.19	3.31	3.04
12:00 PM	865	34.9	44	17.63	0.19	3.35	3.04
12:30 PM	916	36.3	44	17.89	0.18	3.22	3.03
1:00 PM	930	35.4	45	16.38	0.21	3.44	2.98
1:30 PM	919	35.8	44	16.71	0.21	3.51	2.99
2:00 PM	892	43.6	46	16.57	0.21	3.48	3.04
2:30 PM	890	45.2	49	16.24	0.21	3.41	3.04
3:00 PM	871	35.8	45	20.18	0.17	3.43	2.98
3:30 PM	866	36	46	17.20	0.2	3.44	2.98
4:00 PM	843	36	45	17.58	0.19	3.34	2.97
4:30 PM	770	36.2	46	17.21	0.19	3.27	2.99

4.4 Data Analysis of Module Temperature Versus Power Output

To analyze the data in the previous table, this study will focus on the relationship between the module temperature of those three panels and the power produced. Temperature significantly affects solar panel voltage and current, with higher temperatures resulting in reduced energy production. Three PV modules were used with different setups to compare the results obtained. The first solar panel, labeled as Panel A, operated standalone. The second panel, labeled Panel B, incorporated a STEG with a heatsink and DC fan. The third panel, labeled as Panel C, included the entire STEG system with an aluminium concentrator, as shown in Table 5. In this study, maintaining the solar panel's temperature is crucial to prevent efficiency loss. Figure 7 illustrates the graph analysis of module temperature versus output power.

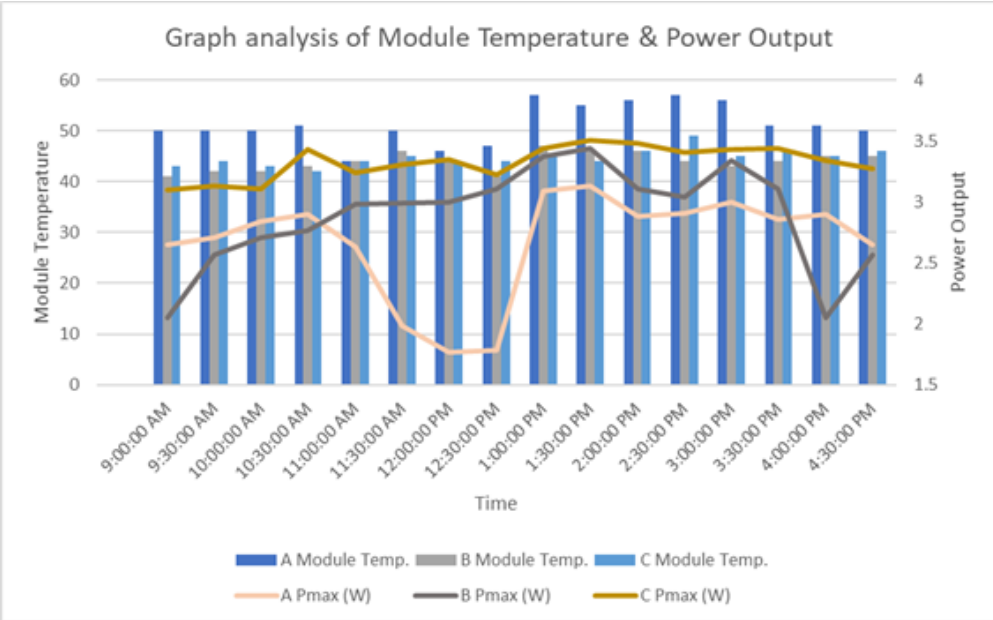


Fig. 7. Graph analysis of module temperature and power output

Table 5
Data of module temperature and power output from PV panel

Time	Panel A		Panel B		Panel C	
	Module Temp (°C)	P_{max} (W)	Module Temp (°C)	P_{max} (W)	Module Temp (°C)	P_{max} (W)
9:00 AM	50	2.65	41	2.05	43	3.1
9:30 AM	50	2.71	42	2.57	44	3.13
10:00 AM	50	2.84	42	2.71	43	3.11
10:30 AM	51	2.9	43	2.77	42	3.43
11:00 AM	44	2.63	44	2.98	44	3.24
11:30 AM	50	1.98	46	2.99	45	3.31
12:00 PM	46	1.77	44	3.00	44	3.35
12:30 PM	47	1.78	41	3.11	44	3.22
1:00 PM	57	3.09	47	3.37	45	3.44
1:30 PM	55	3.13	46	3.44	44	3.51
2:00 PM	56	2.88	46	3.11	46	3.48
2:30 PM	57	2.91	44	3.04	49	3.41
3:00 PM	56	3.00	43	3.34	45	3.43
3:30 PM	51	2.86	44	3.11	46	3.44
4:00 PM	51	2.9	45	2.05	45	3.34
4:30 PM	50	2.65	45	2.57	46	3.27

There is a general trend of increasing and decreasing in maximum power as it correlates with the module's temperature [11]. However, Panel C exhibits the most outstanding performance compared to Panels A and B, as illustrated in Figure 4. For instance, in Panel A, the maximum power at 12:00 PM is 1.77W when the module temperature is 46°C. Subsequently, it increases to 3.13W at 1:30 PM as the module temperature rises to 55°C. Similar to Panel B with the heat sink & DC fan, at 9:00 AM, the maximum power reached 2.05W when the module temperature was 41°C and increased to

3.34W at 3:00 PM when the module temperature was 43°C. However, the performance of PV panel C with a concentrating system is shown as decent value compared to PV panels A & B as it produces higher power output starting from 9:00 AM. The maximum power is at 3.1W with a module temperature of 43°C and gradually increasing to 3.51W with a temperature of 44°C at 1:30 PM.

4.5 Data Analysis of Irradiance Versus Power Output

Table 6 presents the irradiance and power output data from the PV panel, similar to the previous table. Panel A denotes the first solar panel operating standalone. Panel B integrates a STEG with a heatsink and DC fan, while Panel C encompasses the entire STEG system with an aluminium concentrator.

Table 6
Data of irradiance and power output from PV panel

Time	Panel A		Panel B		Panel C	
	Irradiance (W/m^2)	P_{max} (W)	Irradiance (W/m^2)	P_{max} (W)	Irradiance (W/m^2)	P_{max} (W)
9:00 AM	492	2.65	645	2.05	718	3.1
9:30 AM	575	2.71	668	2.57	722	3.13
10:00 AM	602	2.84	757	2.71	779	3.11
10:30 AM	603	2.9	792	2.77	815	3.43
11:00 AM	684	2.63	807	2.98	830	3.24
11:30 AM	709	1.98	842	2.99	878	3.31
12:00 PM	807	1.77	855	3.00	865	3.35
12:30 PM	821	1.78	857	3.11	916	3.22
1:00 PM	789	3.09	866	3.37	930	3.44
1:30 PM	805	3.13	855	3.44	919	3.51
2:00 PM	829	2.88	865	3.11	892	3.48
2:30 PM	842	2.91	816	3.04	890	3.41
3:00 PM	807	3.00	793	3.34	871	3.43
3:30 PM	821	2.86	720	3.11	866	3.44
4:00 PM	722	2.9	732	2.05	843	3.34
4:30 PM	729	2.65	705	2.57	770	3.27

As observed in the graph analysis of irradiance and power output in Figure 8, Panel C consistently maintains the highest irradiance values from 9:00 AM to 4:30 PM compared to Panels A and B. The power output for Panel C directly correlates with irradiance throughout this period. Conversely, for Panels A and B, irradiance gradually increases and aligns with the power output until 2:00 PM. It is evident that from 9:00 AM to 2:00 PM, the irradiance and power output of all three study panels increased in accordance with theoretical expectations.

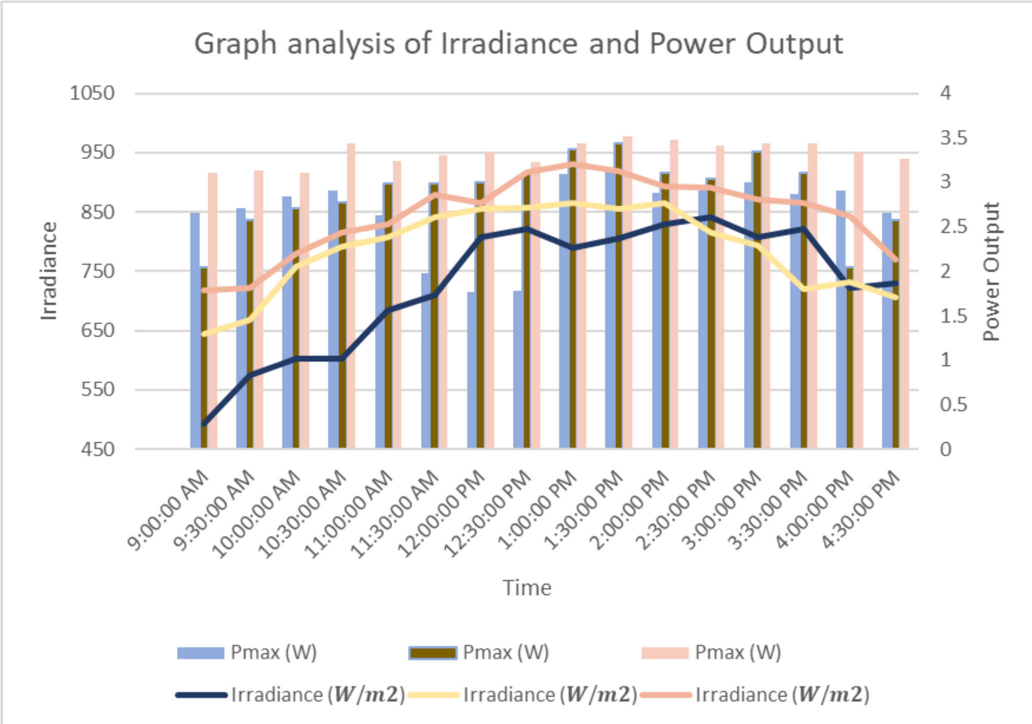


Fig. 8. Graph analysis of irradiance and power output

4.6 The Efficiency of PV Panels

As stated in this study's objectives, the solar panel's efficiency will be observed thoroughly. It can be improved by placing a cooling system and concentrator. There are three conditions for solar panels, with the first being operated standalone. The second panel incorporated a STEG with a heatsink and DC fan. The third panel included the entire STEG system with an aluminium concentrator. The efficiency of each solar panel was calculated using the formula stated in Eq. (3). Table 7 below shows the efficiency of solar panels.

Table 7
Efficiency of solar panel

	PV Standalone	STEG with a heatsink and DC fan.	STEG with a heatsink, DC fan & aluminium concentrator
Pmax (W)	3.13	3.44	3.51
Efficiency	9.21%	10.11%	10.23%

The irradiance used is at 1000W/m2 at STC, and the area for the PV panel is 0.2m x 0.17m. The efficiency of solar panels equipped with a STEG system, heat sink, DC fan, and aluminium concentrator demonstrates the highest percentage compared to the PV standalone configuration and PV with STEG system [29]. Comparing the PV standalone system to the STEG with a concentrator setup reveals higher efficiency due to the improved cooling and concentrator system. However, the efficiency of the STEG system is slightly lower than the third system.

5. Conclusions

This study shows that maintaining the solar panel at an ideal working temperature can significantly impact its performance. The panel's temperature can be effectively regulated by incorporating a cooling system. It was observed that lower temperatures corresponded to higher output power. The study thoroughly investigated the influence of the developed system on power output, with a specific focus on the efficiency and performance of monocrystalline solar panels. Integrating a heatsink, thermoelectric generator, and aluminium foil as a reflector presented an innovative approach to enhance the output of photovoltaic modules. All objectives have been achieved, and the efficiency is increasing gradually according to the improvement of the system. Nonetheless, the cooling system proves to be effective, and it may be recommended to optimize the design of the concentrator further to achieve the optimum power output.

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