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OBTAINING OPTIMAL CONNECTION COMBINATIONS FOR THERMOELECTRIC COOLER (TEC) DEVICES USED FOR ELECTRICITY GENERATION FROM PHOTOVOLTAIC (PV) PANEL WASTE HEAT

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ABSTRACT
The photovoltaic (PV) system with thermoelectric generators (TEG), in which the PV system is cooled by converting part of its waste heat into electricity using the Seebeck effect, is gaining ground. Thermoelectric coolers (TECs), which are Peltier modules, can operate as generators when a temperature gradient is applied. In this research, TECs were used because of their low cost and dual functionality. A water cooling system for the TECs' cold sides was developed. A total of nine (9) TECs were used. Four (4) possible connections were made, consisting of various series-parallel combinations to measure the currents and voltages. These were observed and compared with the temperature differentials. The hot sides of the TECs were glued to the back of the PV panel. Data were collected for 4 days. The four (4) electrical connections of the nine (9) TECs glued to the back of the PV panel were tested for 1 day. The following parameters were measured for PV-TEC: load voltages (V_L), load currents (I_L), Temperatures of the TEC hot and cold sides (TH and TC), and time (t). The output power (P_o) and temperature difference ($\Delta T=T_H-T_C$) were calculated. The highest TEC output power was P_o=269.875mW at temperature difference ΔT=23.40°C. Its connection configuration was three sets of 2TECs connected in series, then connected in parallel, and all in series with 3 other TECs. It shows that P_o is directly proportional to ΔT. It is recommended that the number of TECs and the PV panel size be increased.

Keywords: Seebeck effect, Peltier effect, Thermoelectric generators, Thermoelectric coolers and Electricity generation.

INTRODUCTION
The integration of thermoelectric technology with photovoltaic (PV) systems has recently attracted considerable attention as an innovative approach for improving solar energy utilization. In this approach, thermoelectric generators (TEGs) were incorporated into PV systems to convert a portion of the heat energy typically lost by solar panels into useful electrical energy via the Seebeck effect (He *et al.*, 2021). The effect was first discovered in 1820 by Thomas Seebeck; it describes the production of an electrical potential when two dissimilar conductive materials experience a temperature difference between their contact points (Renge *et al.*, 2017).

This process occurs when charge carriers within thermoelectric materials such as bismuth telluride move from the hotter region toward the cooler region, producing electrical energy in the process (Darkwa *et al.*, 2019). Because thermoelectric devices contain no moving parts, they are durable, reliable, and relatively economical for long-term applications (Hasan *et al.*, 2025).

The thermoelectric phenomenon describes the direct relationship between heat energy and electrical energy in certain conductive materials. Three fundamental effects are commonly associated with thermoelectric behavior, namely the Seebeck effect, the Peltier effect, and the Thomson effect (Pratama & Saraswati, 2023).

The Seebeck effect explains the direct generation of electrical voltage when two unlike conductive materials are connected within a closed electrical circuit and subjected to a temperature difference. As shown in Figure 1, when one junction is exposed to a higher temperature while the other remains at a relatively lower temperature, charge carriers naturally begin to move from the hotter region toward the colder region. This movement occurs because particles at the higher temperature possess greater thermal energy than those at lower temperatures and develop an electrical potential difference (Electrical for Us, 2016).

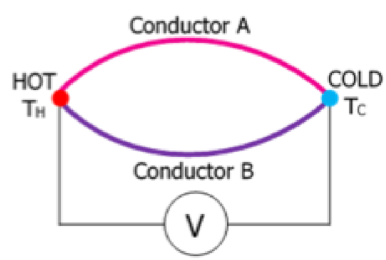

Figure 1: Principle of the Seebeck effect.

The incorporation of thermoelectric generators (TEGs) inside the PV panel must be made such that the TEG sides (i.e., hot and cold) are between two sources of different temperatures. The hot side of the TEG must have good contact with the heat source (Pintanel *et al.*, 2021). The cold side must also be in good contact with a cooling source, such as water via a heat sink. The water must be at its lowest possible temperature (Bayod-Rújula *et al.*, 2019).

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Studies have shown that integrating TEGs with PV panels creates an opportunity to recover part of the heat energy generated by the panel and convert it into additional electrical energy. In hybrid PV-TEG systems, excess heat that would otherwise be wasted can be used to improve the system's overall energy output (Hasan *et al.*, 2025).

Thermoelectric coolers (TECs), commonly designed for cooling purposes, operate based on the Peltier effect. However, these same devices can also generate electrical energy when exposed to temperature differences across their surfaces. Under such conditions, TECs function according to the Seebeck principle and can therefore be utilized for experimental electricity generation (Renge *et al.*, 2017).

Thermoelectric coolers (TECs) represent another alternative for experimental electricity generation. Although TEC modules are primarily manufactured for cooling applications using the Peltier effect, they can also generate electricity when subjected to temperature differences (Shoeibi *et al.*, 2022).

TEG OPEN CIRCUIT VOLTAGE (V_{OC})

The performance of a thermoelectric generator largely depends on the temperature difference maintained between its hot and cold surfaces. One important parameter commonly used in evaluating thermoelectric performance is the dimensionless figure of merit known as ZT. It is mathematically represented as:

$$ZT = \frac{\alpha^2 \sigma}{\lambda} T \qquad (1)$$

Where,

α= Seebeck coefficient.
σ = Electrical conductivity.
λ= Thermal conductivity.
T= Temperature in kelvin

If TH represents the temperature at the hot surface and that at the cold surface is represented by T_C, then the temperature difference can be expressed as:

$$\Delta T = T_H - T_C \qquad (2)$$

For p-type and n-type semiconductor materials possessing Seebeck coefficients of α_p and α_n, respectively, the open-circuit voltage generated by the module can be determined using the expression:

$$V_{open} = (\alpha_p - \alpha_n)\, \Delta T \qquad (3)$$

This relationship shows that the electrical output of a thermoelectric generator is directly influenced by the magnitude of temperature difference across the device (Renge *et al.*, 2017).

In this work, the excess heat generated at the back of a PV panel was converted into electricity using thermoelectric coolers (TECs). A cooling system design for the cold sides of the TECs and a system that converts the excess heat at the back of the PV panel to electricity using TECs were developed. The study was conducted in Jaji, Kaduna State, Nigeria, a high-solar-radiation tropical savannah region. Environmental conditions, including 29–38°C temperatures, adequate solar irradiance, and favorable thermal gradients, made the location suitable for evaluating the performance of a hybrid photovoltaic–thermoelectric cooler (PV–TEC) system.

Apart from conventional TEGs, researchers have also explored the possibility of using TECs as alternative devices for electricity generation. Akashah *et al. (2019) together with Wan Jamaludin et al. (2020)* carried out experimental investigations to determine the feasibility of employing TECs as renewable energy conversion devices. Their experimental setup utilized TEC modules identified as TEC1-12706. The results showed that when two TEC modules were connected in series with a 200Ω load resistor, the electrical power generated was approximately 416 μW. Under parallel connection conditions, output power increased significantly to about 100 mW when the temperature difference across the modules reached 7°C. These observations agreed closely with earlier findings reported by Coskun *et al.* (2017).

Similarly, Renge *et al.* (2017) investigated methods of maximizing electrical output from TEC-12706 modules by exposing them to industrial waste heat and automobile exhaust heat sources. Their prototype system successfully produced output voltages of approximately 3.05 V and 2.68 V when subjected to temperature differences of 80°C and 67°C, respectively. Their results further demonstrated that thermoelectric coolers, although originally designed for cooling, can still deliver useful electrical energy under appropriate operating conditions.

MATERIALS AND METHODS

The experiment was conducted for 4 days. The experiment ran from 8:00 to 17:00 each day. Readings were taken at one-hour intervals.

A. *Materials*

The materials used in the experimental set-up of this study were in two categories: materials for PV-TEC installation and a water-cooling system.

1. Materials for PV-TEC System

The list of items used is displayed in Table 1, while Plate 1 (a) and (b) show the PV panel and TEC module, respectively:

Table 1: Materials for PV-TEC and control PV panel with their quantity.

S/N	NAME OF ITEM	QUANTITY
1.	Polycrystalline PV panel (10W)	1
2.	Thermoelectric coolers (TEC1-12706)	9
3.	Aluminium heat sinks (40mm by 40mm)	9
4.	Resistor (100Ω, 0.125W)	1
5.	R & D MT-30 Digital Luxmeter	1
6.	3 channels MTM-380SD Temperature Data Recorder	1
7.	DT-9205A Digital multimeter (Ammeter)	1
8.	DT-9801 Digital multimeter (Voltmeter)	1
9.	Time clock	1

2. Materials for Water Cooling System

The items for the cooling of TEC's cold sides as well as cooling the panel attached to it were:

(i) Two (2) 20-liter plastic water tanks.

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(ii) One (1) control tap.
(iii) Cooling trough; it supports the heat sinks, TECs and the PV panel.
(iv) Water hose.
(v) A wooden stand of height 2m to support the water-cooling tank and a table of height 1m to support the PV-TEC with the cooling trough.
(vi) Miscellaneous: adhesive, hammer, pair of scissors.

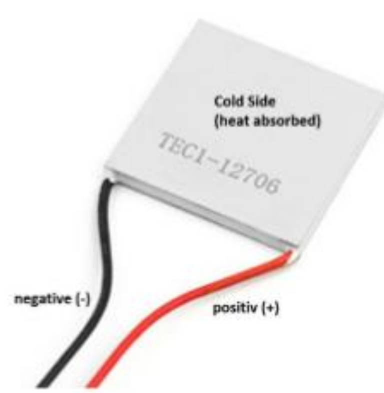
B. Specification of TEC

Table 2: TEC module specification.

TEC Model	TEC1-12706
Voltage:	12V
V_{max}:	15.4V
I_{max}:	6A
Q_{max}:	92W
Internal resistance:	1.98Ω +/- 10%
Dimensions:	40mm x 40mm x 3.6mm
Type:	Cooling cell
Usage:	Refrigerator, Warmer and Generator
Maximum operating temperature:	138 ºC
Life expectancy:	200,000 hours

(a)

Plate 1: (a) PV panel



(b)

(b) TEC Module type TEC1-12706

The experimental set-up was as presented in Figure 2.

C. Experimental Set-up for the PV-TEC System

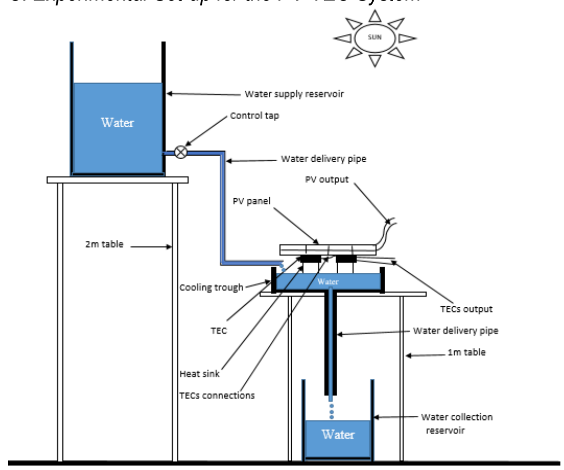


Figure 2: Experimental set-up for the PV-TEC system

The TECs were sandwiched between the back of the PV panel and the heat sinks, then placed in the cooling trough. The hot sides of the TECs were in good contact with the back of the PV panel and the cold sides in good contact with the heat sinks. Water flows through the delivery pipe and the cooling trough to cool the heat sinks, which in turn cool the TECs' cold sides. Warm water was displaced to the water collection reservoir at the bottom of the 1 m table. At one-hour intervals, water from the collection reservoir was manually returned to the supply reservoir, and ice blocks were added to lower its temperature further.

The temperature difference between the hot and cold sides of the TECs generates electricity.

D. TECs Electrical Connections with their Attachments to the PV panel and their connections to Electrical Measuring Instruments

Choosing the appropriate electrical connections and assembly of TEG modules to obtain the appropriate voltage is an issue. Most PV-TEG systems link many thermoelectric modules in series and parallel arrays to achieve the necessary power level (Qasim *et al.*, 2022).

In this work, a total of nine (9) TECs were used based on choice. Four (4) possible connections were made as shown in Figures 3 to 6.

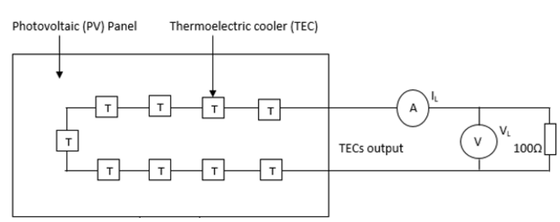


Figure 3: Diagram for all TECs connected in series and glued to the back of the PV panel.

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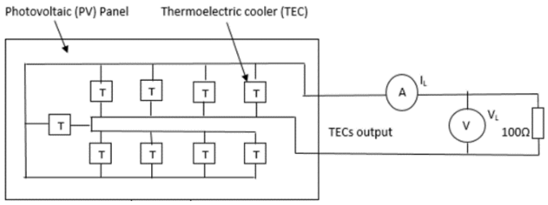

Figure 4: Diagram of all TECs connected in parallel and glued to the back of the PV panel.

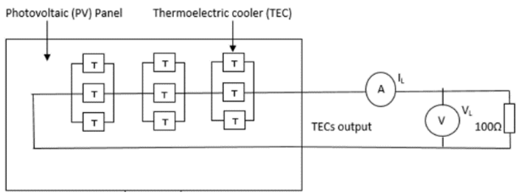

Figure 5: Diagram of three sets of 3TECs connected in parallel and in series with each other, then glued to the back of the PV panel.

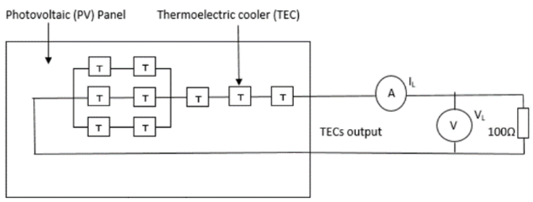

Figure 6: A diagram with three sets of 2TECs connected in series and then connected in parallel with each other and all in series with 3 other TECs, then glued to the back of the PV panel.

Data were collected for 4 days for the four (4) electrical connections of the nine (9) TECs glued to the back of the PV panel; each was tested for 1 day. Readings were taken at 1-hour intervals between 8:00 and 17:00 hours each day. The connections were as follows;

(i) All TECs connected in series (day 1).
(ii) All TECs connected in parallel (day 2).
(iii) Three sets of 3TECs connected in parallel and in series with each other (day 3).
(iv) Three sets of 2TECs connected in series and then connected in parallel with each other and all in series with 3 other TECs (day 4).

The following parameters were measured:

(i) load voltages (V_L)
(ii) load currents (I_L) for the various TEC connections.
(iii) Temperatures of TEC hot sides (T_H) and cold sides (T_C).

The following parameters were computed from the raw data:

(i) For the TEC connections in which a 100Ω load resistor was connected across its output, the output power is given as:

$$P_o = V_L \times I_L \quad (4)$$

(ii) The temperature difference between the hot and cold sides of the TECs is given as:

$$\Delta T = T_H - T_C \quad (5)$$

RESULTS AND DISCUSSION

The graphs of output power (P_o) against time (t), temperature difference (ΔT) and load voltage (V_L) against time (t) and temperature difference (ΔT) and P_o against time (t) of the four different 9 TECs connections were plotted using Origin 2018 software as follows:

1. *The graphs of output power (P_o) for day 1, 2, 3 and 4 versus t were studied and presented as shown in Figure 4.*
2.

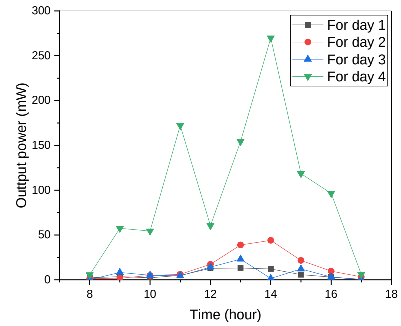

Figure 4: Output power (P_o) for day 1, 2, 3 and 4 versus time (t).

The graph in Figure 4 shows the relationship between the four TEC connections for days 1, 2, 3 and 4 and time. Day 4 has the highest P_o, due to a mix of series and parallel TEC connections and the largest temperature differences (ΔT) compared to the other days. While most PV-TEG systems link many thermoelectric modules in series and parallel arrays to achieve the necessary power level, this approach is not practical. The higher the temperature difference between the hot and cold sides of the TEG, the higher the output power (Qasim *et al.*, 2022).

2. The graphs of temperature difference (ΔT) and TECs load voltage (V_L) versus time (t) for days 1, 2, 3 and 4 are presented in Figures 6 to 9.

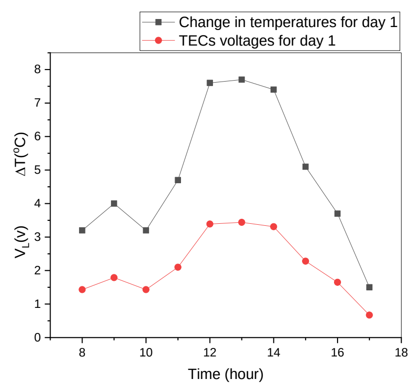

Figure 6: Temperature difference (ΔT) and TECs load voltage (V_L) versus time (t) for day 1.

The relationship between TECs load voltage (V_L) and temperature differences between its hot and cold sides (ΔT) is shown in Figure 6 for day 1. It clearly shows that V_L is directly proportional to ΔT, i.e., an increase in ΔT causes an increase in V_L and vice versa. An increase or decrease in temperature difference between the hot and cold sides of the TEC will also cause an increase or decrease in the voltage produced by the Seebeck effect, respectively

(Shoeibi *et al*., 2022). The highest value of V_L is above 3V.

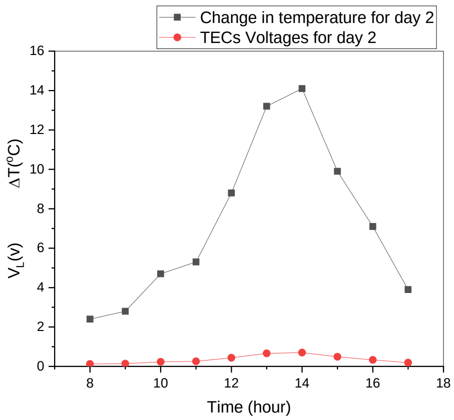

Figure 7: Temperature difference (ΔT) and TECs load voltage (V_L) versus time (t) for day 2.

The graph in Figure 7 shows that the VL and ΔT curves for the TECs connection have a slightly similar pattern. This means that a large increase in ΔT causes a small increase in VL, and vice versa. The reason is that all 9 TECs were connected in parallel, and the total voltage in the circuit was the voltage of one TEC. The highest value of V_L is about 0.5V.

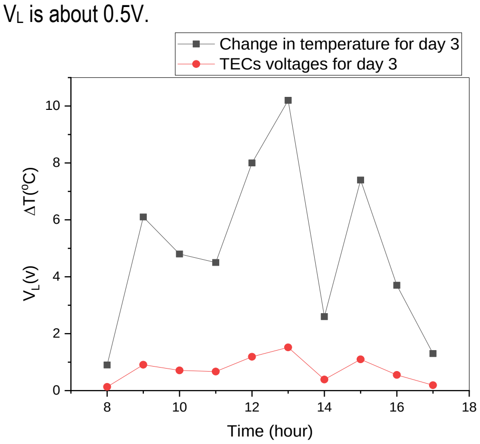

Figure 8: Temperature difference (ΔT) and TECs load voltage (V_L) versus time (t) for day 3.

The graph in Figure 8 shows the curves V_L and ΔT for the TECs connection on day 3. It shows that as ΔT increases, V_L also increases and vice versa. Therefore, ΔT is directly proportional to V_L. The highest value of V_L is above 1.5V.

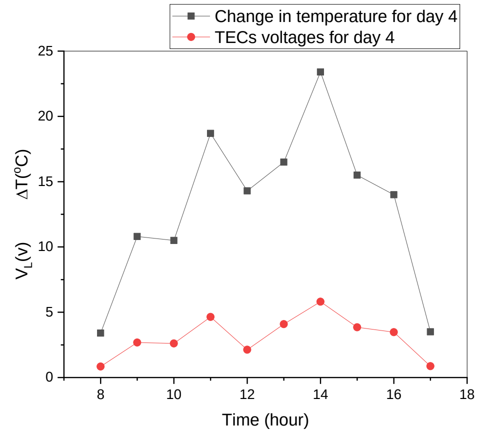

Figure 9: Temperature difference (ΔT) and TECs load voltage (V_L) versus time (t) for day 4.

The graph in Figure 9 shows that the VL and ΔT curves for the TECs connection follow the same pattern. It simply means that as ΔT increases, V_L also increases and vice versa. The highest value of V_L is above 5V.

3. The graphs of temperature difference (ΔT) and TECs output power (P_o) versus time (t) for days 1, 2, 3 and 4 are presented in Figures 10 to 13.

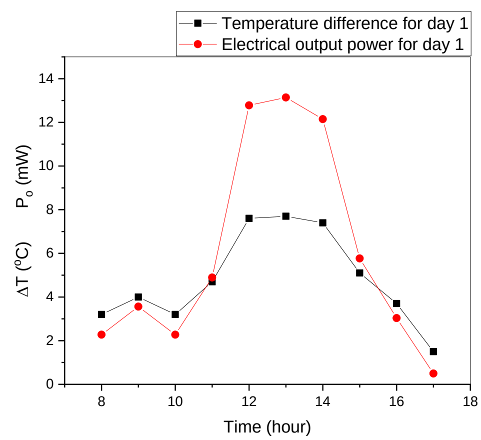

Figure 10: A graph of ΔT and P_o against t for day 1.

For day 1, Figure 10 shows high P_o between 12:00 and 14:00 hours because ΔT is at its maximum during this period. It clearly shows that P_o is directly proportional to ΔT.

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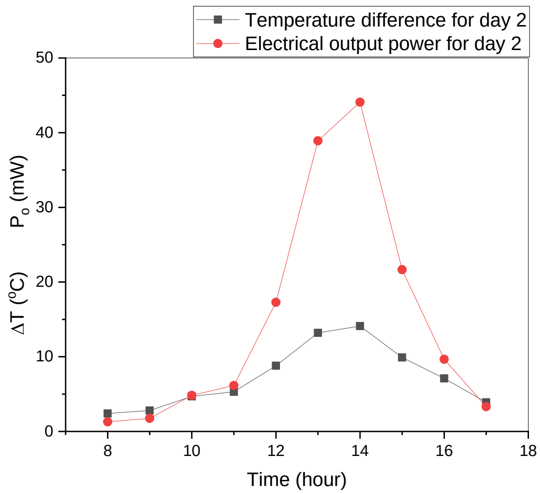

Figure 11: A graph of ΔT and P_o against t for day 2.

For day 2, Figure 11 shows a high Po at 14:00 hours because ΔT is at its maximum during this period. It clearly shows that P_o is directly proportional to ΔT.

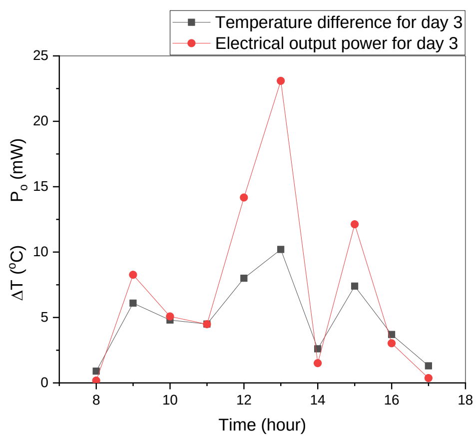

Figure 12: A graph of ΔT and P_o against t for day 3.

The graph in Figure 12 shows the variations in this electrical power, which depend on the magnitudes of the voltages and currents generated. These variations result from fluctuations in ΔT with time. Also, P_o is directly proportional to ΔT as seen in Figure 12.

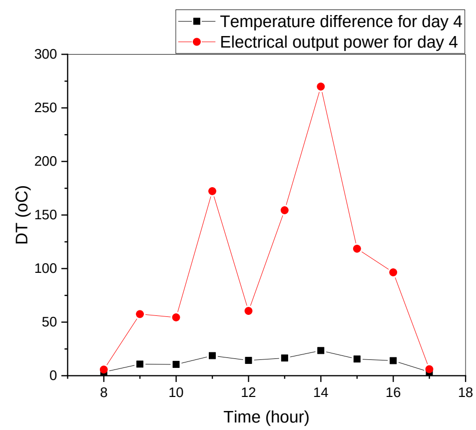

Figure 13: A graph of ΔT and P_o against t for day 4.

The graph of Figure 13 shows the variations in this electrical power, which depend on the magnitudes of voltages and currents generated. These variations result from fluctuations in ΔT over time. Also, P_o is directly proportional to ΔT, as seen in Figure 13. This combination of TECs proved very effective in power generation because it has the highest P_o of 269.875mW.

4. Comparison of TECs combinations with the highest output power (P_L) per day.

The highest output power for the TECs connections for each day is shown in Table 3, which gives the temperature differences (ΔT) and time of the day.

Table 3: Highest output power (P_o) for the TECs connections for each day.

Day	Time (hour)	TECs connections	Highest ΔT (°C)	V_L (V)	I_L (mA)	P_o (mW)
1	13.00	All TECs in series	7.70	3.44	3.82	13.141
2	14.00	All TECs parallel	14.10	0.70	62.97	44.079
3	13.00	Three sets of 3TECs connected in parallel and in series with each other	10.20	1.52	15.19	23.089
4	14.00	Three sets of 2TECs connected in series and then	23.40	5.81	46.45	269.875

	connected in parallel with each other and all in series with 3 other TECs

The bar graph showing comparison between highest P_o and ∆T for each day was as presented in Figure 14.

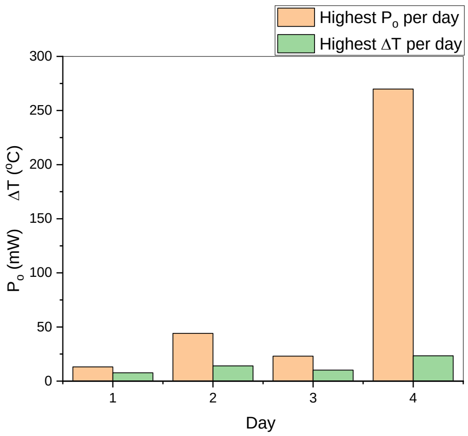

Figure 14: Bar graph comparing highest P_o and ∆T for each day.

From Figure 14, the setup for day 4 has the highest output power, Po = 269.875 mW. This is because its temperature difference is the highest among others, i.e. ∆, T = 23.40 °C. The connection combination was three sets of 2TECs connected in series, then connected in parallel with each other, and all in series with 3 other TECs.

Conclusion

The research was carried out successfully, in which the excess heat generated at the back of a PV panel was converted into electricity using thermoelectric coolers (TECs). The design and development of a cooling system for the cold sides of the TECs and, in turn, cooling the PV panel by convection was achieved. The result of this research work shows that TECs can serve as a substitute for TEGs in electricity generation. Mixed series and parallel connections of TECs yield higher output power than either series or parallel alone. During the course of this research, extensive experience was gained in this field of study. As a result, it is hereby recommended that the number of TECs and the size of the PV panel be increased, and that another method of cooling the TECs' cold sides be adopted in addition to water cooling.

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APPENDIX

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DAY 1 (14th January, 2022)

Table 4.1: Nine (9) TECs connected in series and glued to the back of PV panel.

TIME (Hour)	V_L(V)	I_L(mA)	P_O(mW)	T_C (°C)	T_H (°C)	ΔT (°C)
8.00	1.43	1.59	2.274	28.60	31.80	3.20
9.00	1.79	1.99	3.562	29.70	33.70	4.00
10.00	1.43	1.59	2.274	30.80	34.00	3.20
11.00	2.10	2.33	4.893	31.90	36.60	4.70
12.00	3.39	3.77	12.780	31.70	39.30	7.60
13.00	3.44	3.82	13.141	33.50	41.20	7.70
14.00	3.31	3.67	12.148	33.20	40.60	7.40
15.00	2.28	2.53	5.768	33.80	38.90	5.10
16.00	1.65	1.84	3.036	34.50	38.20	3.70
17.00	0.67	0.74	0.496	33.80	35.30	1.50

DAY 2 (28th January, 2022)

Table 4.5: Nine (9) TECs connected in parallel and glued to the back of PV panel.

TIME (Hour)	V_L(V)	I_L(mA)	P_O(mW)	T_C (°C)	T_H (°C)	ΔT (°C)
8.00	0.12	10.72	1.286	24.70	27.10	2.40
9.00	0.14	12.50	1.750	27.30	30.10	2.80
10.00	0.23	20.99	4.828	28.10	32.80	4.70
11.00	0.26	23.67	6.154	30.20	35.50	5.30
12.00	0.44	39.30	17.292	28.60	37.40	8.80
13.00	0.66	58.96	38.914	27.90	41.10	13.20
14.00	0.70	62.97	44.079	31.20	45.30	14.10
15.00	0.49	44.22	21.668	31.70	41.60	9.90
16.00	0.33	29.28	9.662	31.60	38.70	7.10
17.00	0.19	17.42	3.310	31.30	35.20	3.90

DAY 3 (4th February, 2022)

Table 4.9: Sets of three (3) TECs connected in parallel and in series with each other and glued to the back of PV panel.

TIME (Hour)	V_L(V)	I_L(mA)	P_O(mW)	T_C (°C)	T_H (°C)	ΔT (°C)
8.00	0.13	1.34	0.174	26.60	27.50	0.90
9.00	0.91	9.08	8.263	28.60	34.70	6.10
10.00	0.71	7.15	5.077	30.40	35.20	4.80
11.00	0.67	6.69	4.482	28.60	33.10	4.50
12.00	1.19	11.91	14.173	29.80	37.80	8.00
13.00	1.52	15.19	23.089	30.90	41.10	10.20
14.00	0.39	3.87	1.509	31.20	33.80	2.60
15.00	1.10	11.02	12.122	30.80	38.20	7.40
16.00	0.55	5.51	3.031	30.70	34.40	3.70
17.00	0.19	1.94	0.369	29.50	30.80	1.30

DAY 4 (11th February, 2022)

Table 4.13: Two sets of three (3) TECs connected in series and in parallel with each other and connected in series with three (3) other TECs and glued to the back of PV panel.

TIME (Hour)	V_L(V)	I_L(mA)	P_O(mW)	T_C (°C)	T_H (°C)	ΔT (°C)
8.00	0.84	6.75	5.670	28.10	31.50	3.40
9.00	2.68	21.44	57.450	28.40	39.20	10.80
10.00	2.61	20.84	54.392	30.60	41.10	10.50
11.00	4.64	37.12	172.237	33.70	52.40	18.70
12.00	2.13	28.38	60.449	34.10	48.40	14.30
13.00	4.09	37.75	154.398	35.70	52.20	16.50
14.00	5.81	46.45	269.875	35.80	59.20	23.40
15.00	3.85	30.77	118.465	36.90	52.40	15.50
16.00	3.47	27.79	96.431	35.80	49.80	14.00
17.00	0.87	6.95	6.045	33.40	36.90	3.50