

# Experimental Study of a TEG-Based Passive Cooling and Energy Harvesting System for Enhancing Photovoltaic (PV) Performance

Denny Haryanto Sinaga<sup>1</sup>, Arwadi Sinuraya<sup>2</sup>, Muhammad Aulia Rahman Sembiring<sup>3</sup>, Dian Putra Saragi<sup>4</sup>, Dito Yudisthira Nugroho<sup>5</sup>, Yusuf Sihombing<sup>6</sup>

{ [denny.sinaga@unimed.ac.id](mailto:denny.sinaga@unimed.ac.id)<sup>1</sup>, [arwadisinuraya@gmail.com](mailto:arwadisinuraya@gmail.com)<sup>2</sup>, [marsembiring@unimed.ac.id](mailto:marsembiring@unimed.ac.id)<sup>3</sup>, [dianpsaragi@unimed.ac.id](mailto:dianpsaragi@unimed.ac.id)<sup>4</sup>, [ditoyudisthiranugroho@mhs.unimed.ac.id](mailto:ditoyudisthiranugroho@mhs.unimed.ac.id)<sup>5</sup> [sihombingyusuf4@gmail.com](mailto:sihombingyusuf4@gmail.com)<sup>6</sup> }

Department of Electrical Engineering, Faculty of Engineering, Universitas Negeri Medan, Indonesia<sup>123456</sup>,

Jl. Willem Iskandar Pasar V, Medan, North Sumatera, Indonesia

**Abstract.** This research investigates the integration of thermoelectric generator (TEG) modules into photovoltaic (PV) panels as a passive cooling strategy to improve thermal management and electrical performance. A total of 42 TEG modules were mounted on the back surface of a 100 Wp monocrystalline photovoltaic panel using thermal adhesive and a passive aluminum heatsink. Outdoor experimental tests showed that TEG integration reduced the PV surface temperature from 61.44°C to 56.18°C, representing a reduction of 8.06%. This temperature reduction contributed to stabilizing the open-circuit voltage (Voc) and reducing thermal losses. Peak solar irradiation was recorded at 1:30 p.m., generating 118.98 W for the PV–TEG system and 111.53 W for the conventional PV system. The peak power of the PV–TEG system increased by approximately 6.68%, a difference of 7.45 W compared to the conventional PV system. The TEG array generated a peak power of 2.398 W by utilizing the waste heat from the PV surface. These findings demonstrate that TEG-assisted cooling offers a practical and sustainable approach to improving PV module performance under real-world operating conditions.

**Keywords:** Photovoltaic, Thermoelectric Generator (TEG), PV–TEG Hybrid System, Thermal Management, Energy Harvesting.

## 1 Introduction

The growing global demand for energy, driven by population growth and industrial development, has raised concerns regarding the continued dependence on fossil fuels. In addition to being finite resources, fossil fuels are a major contributor to greenhouse gas emissions, which significantly impact global climate change [1]. Renewable energy technologies, particularly photovoltaic (PV) systems, have been widely recognized as strategic solutions to meet future energy needs [2]. However, the energy conversion efficiency of conventional PV modules remains limited, primarily due to elevated operating temperatures that reduce their performance [3]. This problem arises from the accumulation of heat on the panel

surface, which is not effectively utilized. Typically, only 10–15% of incident solar energy is converted into electricity, while the majority is dissipated as waste heat to the environment without recovery [4].

The integration of thermoelectric generators (TEGs) into PV systems has emerged as an innovative approach to mitigate efficiency losses caused by thermal buildup on solar panel surfaces [5]. TEGs are solid-state devices based on the Seebeck effect, which generates electrical voltage when a temperature gradient exists between the hot and cold sides of the material. When installed on the rear side of a PV panel, the excess heat generated by the solar cells can be transferred to the TEG modules [6]. This process not only lowers the panel's operating temperature—thereby improving PV electrical efficiency—but also enables the conversion of waste thermal energy into supplemental electrical power.

This study investigates the design and performance of a TEG-based passive cooling system integrated into a monocrystalline PV module. The primary objectives are to evaluate the thermal effectiveness of the cooling configuration and quantify its impact on PV efficiency enhancement. The system employs a direct coupling method, where 42 TEG modules are mounted on the rear surface of a 100 Wp solar panel using thermal interface material and passive aluminum heatsinks. Key performance indicators, including temperature reduction, thermal response characteristics, and efficiency improvements, are analyzed to assess the viability and benefits of the PV–TEG hybrid system.

## **2 Methodology**

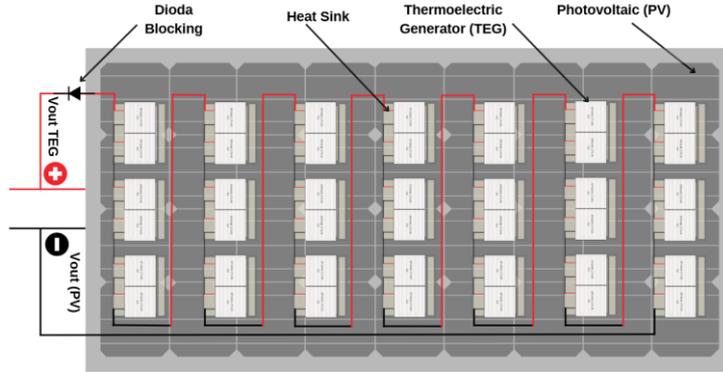
This research employed an experimental approach focused on the design, implementation, and performance evaluation of a thermoelectric generator (TEG)-based cooling system for solar panels. The experimental setup was designed to evaluate the impact of surface heat utilization on solar panel efficiency through direct coupling of thermoelectric modules on the rear side of the PV panel. The experiments were conducted between 10.00 AM to 5.00 PM under real tropical outdoor conditions. The research was conducted at the Higher Education Center of Excellence for Science and Technology, the Innovation Centre of Renewable Source and Waste Integration for Sustainable Energy, Universitas Negeri Medan.

### **2.1 System Design and Components**

The experimental setup comprised a monocrystalline PV panel rated at 100 Wp, with dimensions of 1.00 m × 0.67 m, and 42 thermoelectric generator (TEG) modules (type SP1848-27145 SA, 40 × 40 × 3.4 mm). The TEG modules were connected in series to increase the output voltage and were attached to the rear surface of the PV panel using thermally conductive adhesive to ensure efficient heat transfer. To enhance the temperature gradient ( $\Delta T$ ) across the modules, aluminum heatsinks were mounted on the cold side of each TEG, enabling passive cooling through natural convection.

The system employed a direct coupling method, in which the TEGs were directly interfaced with the solar panel without the use of intermediate heat exchangers. The rear surface of the panel served as the heat source, while the aluminum heatsinks facilitated heat dissipation from the cold side to the ambient air. This configuration provided passive cooling of the PV panel while simultaneously harvesting additional electrical energy from the heat flow.

The electrical outputs of both the PV panel and the TEG array were measured independently using digital multimeters and current sensors. A temperature monitoring system was implemented to record the PV surface temperature (with and without TEG), as well as the hot and cold sides of the modules. Solar irradiance was measured with a solar power meter, and ambient temperature was monitored using a digital thermometer. The integration design of the TEG with the PV panel using the direct coupling method is shown in Figure 1.



**Fig. 1.** Integration of thermoelectric generators with solar panels

## 2.2 Data Measurement and Analysis

The research was carried out over 10 consecutive days in an outdoor tropical environment under clear-sky conditions. Data were collected at 30-minute intervals between 10:00 AM and 5:00 PM to capture significant fluctuations in solar irradiance, particularly during midday peak hours. This time range was selected to capture significant fluctuations in solar irradiance, particularly during peak sunlight hours at midday. At each time interval, the recorded parameters included solar irradiance intensity ( $G$ ) in  $W/m^2$ , surface temperature of the solar panel ( $T_p$ ), hot side ( $T_{hot}$ ) and cold side ( $T_{cold}$ ) temperatures, as well as voltage ( $V$ ) and current ( $I$ ) from both the PV and TEG systems. The power output ( $P_{out}$ ) of the solar panel was calculated as the product of open-circuit voltage ( $V_{oc}$ ), short-circuit current ( $I_{sc}$ ), and fill factor ( $FF$ ), based on the characteristics of the solar cell. The power output ( $P$ ) was calculated using the equation (1).

$$P_{Out} = V_{oc} \times I_{sc} \times FF \quad (1)$$

The Fill Factor value for solar cells usually ranges from 0.7 to 0.85, a higher Fill Factor value indicates a better quality solar cell. The equation for the fill factor is shown in equation (2) [7].

$$FF = \frac{V_{oc} - \ln(V_{oc} + 0,7)}{V_{oc} + 1} \quad (2)$$

Where:

- $P_{out}$  = Power output (W)
- $V_{oc}$  = Open circuit voltage (V)
- $I_{sc}$  = Short circuit current (A)

The output power of the thermoelectric generator can be seen from equation (3) [8].

$$P_{TEG} = V_{TEG} \times I_{TEG} \quad (3)$$

Where:

- $P_{TEG}$  = Power output (W)
- $V_{TEG}$  = Open circuit voltage (V)
- $I_{TEG}$  = Short circuit current (A)

The efficiency of a solar panel is a fundamental parameter that indicates the ability of a photovoltaic (PV) module to convert incident solar radiation into electrical energy. In principle, efficiency is defined as the ratio of the electrical power output produced by the PV module to the total solar irradiance incident on its surface. Accordingly, the efficiency of the solar panel can be expressed as shown in Equation (4) [9].

$$\eta_p = \frac{P_{act}}{G \times A_p} \times 100 \quad (4)$$

- $\eta_{pv}$  = Efficiency of the photovoltaic (PV) module
- $P_{act}$  = Output power generated by the PV panel (W)
- $G$  = Solar irradiance intensity (W/m<sup>2</sup>)
- $A_p$  = Surface area of the PV panel (m<sup>2</sup>)

### 3 Results and Discussion

#### 3.1 Experimental Setup

During the measurement process, solar irradiation values were recorded within the range of 121.76 W/m<sup>2</sup> to 1372.2 W/m<sup>2</sup>, while the surface temperature of the photovoltaic panel varied between 32°C and 62°C. This study was conducted to obtain the open-circuit voltage (V<sub>oc</sub>), short-circuit current (I<sub>sc</sub>), solar panel surface temperature (°C), temperature difference (ΔT) across the TEG module, solar irradiation intensity (W/m<sup>2</sup>), and the additional energy generated by the TEG.

Figure 2 illustrates the installation of the TEG modules along with the heatsink, which are mounted on the underside of the photovoltaic panel. The TEG modules were systematically arranged and firmly attached using HY510 thermal glue on the panel surface to ensure effective heat transfer from the solar panel to the TEG modules.

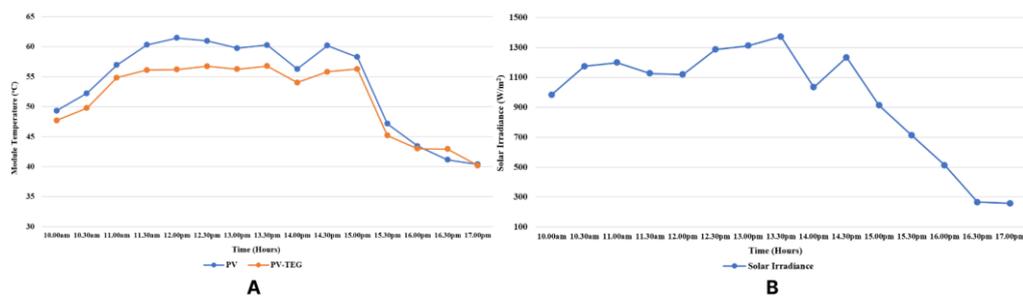


**Fig. 2.** Hybrid PV-TEG systems

### 3.2 Surface Temperature Analysis

The measurement results from 10:00 AM to 5:00 PM demonstrated that integrating thermoelectric generator (TEG) modules on the rear surface of the photovoltaic (PV) panel had a significant impact on the surface temperature characteristics. The PV-TEG system reduced the panel surface temperature from 61.44 °C to 56.18 °C at 12:00 PM Figure 3A, corresponding to a reduction of 5.26 °C, or approximately 8.56%, compared with a conventional PV panel. This passive cooling effect resulted from direct heat absorption by the hot side of the TEG from the PV back surface, combined with passive heat dissipation through the aluminum heatsink on the cold side. The resulting temperature gradient ( $\Delta T$ ) enabled additional electricity generation via the Seebeck effect.

The observed temperature reduction directly enhanced photovoltaic cell efficiency by lowering the operating temperature, thereby decreasing internal resistance and minimizing thermal losses. Moreover, the more stable thermal conditions contributed to maintaining consistent open-circuit voltage ( $V_{oc}$ ), particularly during peak irradiance hours when thermal buildup typically degrades PV performance. Solar irradiance during the measurement period is shown in Figure 3B.



**Fig. 3.** (A) PV module operating temperature (°C) (B) Solar Irradiance (W/m<sup>2</sup>)

### 3.3 Open Circuit Voltage (Voc)

Open-circuit voltage (Voc) measurements conducted between 10:00 AM and 5:00 PM demonstrated that the integration of thermoelectric generator (TEG) modules with photovoltaic (PV) panels consistently outperformed the conventional PV configuration. As shown in Figure 4, the PV–TEG system delivered higher Voc values throughout the observation period. The maximum Voc of the PV–TEG system was 21.52 V at 1:30 PM, compared with 20.28 V for the conventional PV system at the same time. On average, the voltage difference between the two systems ranged from 0.5 to 1.0 V.

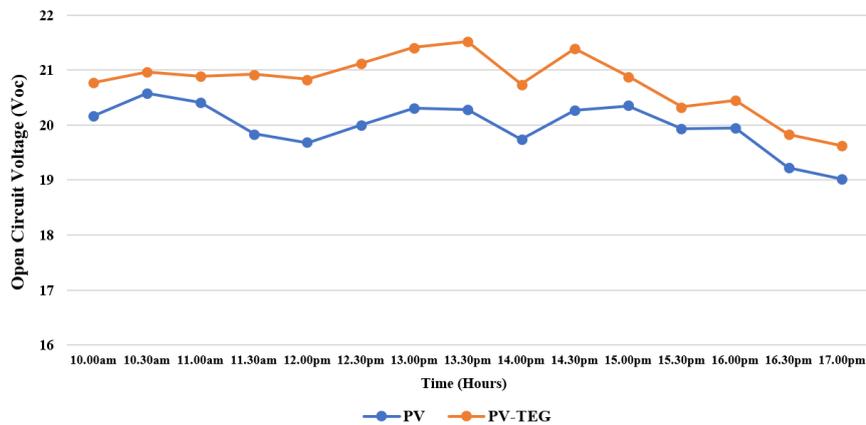
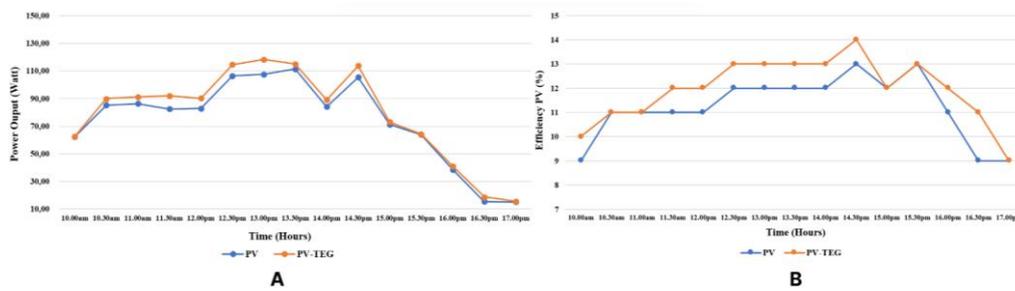


Fig. 4. Open circuit voltage (Voc)

### 3.4 Power Output and Efficiency of PV

Figures 5A and 5B present the transient variations of power output and conversion efficiency, respectively, for the simple PV and hybrid PV–TEG systems during the observation period (10:00 AM–5:00 PM). The PV–TEG system consistently delivered higher output power than the conventional PV system. At 1:30 PM, the PV–TEG system achieved a peak power of 118.98 W compared to 111.53 W for the conventional PV, representing a 6.68% improvement (7.45 W difference). This enhancement is attributed to the passive cooling effect of the TEG modules, which stabilized panel temperature, reduced internal resistance, and improved conversion efficiency.

The performance advantage of the hybrid system was most evident between 11:00 AM and 2:30 PM, coinciding with peak solar irradiance (Figure 5A). Overall, the integration of TEG modules demonstrated clear effectiveness in enhancing the power performance of PV panels under real operating conditions.



**Fig. 5.** (A) Output Power (Watt) (B) Efficiency of PV

### 3.5 Power Output Thermoelectric Generator (TEG)

The TEG system, consisting of 42 series-connected modules, demonstrated stable performance in generating voltage and power from the surface heat of the solar panel. The maximum voltage and power were recorded at 3:00 PM, reaching 21.04 V and 2.40 W, respectively, while the daily average values were 16.38 V and 1.63 W. On a per-module basis, the output was approximately 0.39 V and 0.0387 W. The system performance increased with higher temperature gradients ( $\Delta T$ ) between 10:00 AM and 3:00 PM, but declined sharply after 3:30 PM as solar irradiance decreased. These results indicate that the effectiveness of the system is strongly influenced by the temperature difference and heat dissipation efficiency. With stable operation during daytime hours, the system shows potential as a passive thermal energy harvesting solution in tropical climates. The detailed measurement results of the thermoelectric generator are presented in Table 1.

**Table 1.** Power output thermoelectric generator (TEG)

Time (Hours)	Open-circuit voltage (V)	Power Output (Watt)
10.00am	15.85	1.3948
10.30am	17.83	1.65819
11.00am	20.01	2.14107
11.30am	20.05	2.14535
12.00pm	19.51	2.00953
12.30pm	19.96	2.11576
1.00pm	19.71	2.04984
1.30pm	20.04	2.14428
2.00pm	19.48	2.00644
2.30pm	20.35	2.21815
3.00pm	21.04	2.39856
3.30pm	8.34	0.60048
4.00pm	7.82	0.48484
4.30pm	8.40	0.5712
5.00pm	7.43	0.45323
Average	16.38	1.62611

## 4 Conclusion

This research has demonstrated the successful integration of a Thermoelectric Generator (TEG)-based cooling system with photovoltaic (PV) panels to improve thermal regulation and overall energy performance. Experimental results indicate that the integration of a Thermoelectric Generator (TEG)-based cooling system with photovoltaic (PV) panels can reduce the surface temperature of the PV module by up to 5.26°C, equivalent to a temperature reduction of approximately 8.56% compared to a conventional PV system. This temperature reduction significantly contributes to increasing PV efficiency by stabilizing the output voltage and minimizing thermal losses, especially during peak irradiation periods. The peak power at 1:30 PM was 118.98 W for the PV–TEG system and 111.53 W for the conventional PV system, representing a 6.68% (7.45 W) improvement over the PV–TEG system. The TEG array consisting of 42 series-connected modules achieved a peak power of 2,398 W, with an average daily power of 1,626 W and an average open-circuit voltage of 16.38 V. The average power generated per module was 0.0387 W. These findings confirm that the TEG modules not only function as passive cooling components, but also contribute to additional electrical power by utilizing waste heat through the Seebeck effect.

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