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Designing an Off-Grid System Using Solar Panels and Thermoelectric Generators (TEG) for Renewable Energy Applications

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ABSTRACT

The limited availability of stable electricity in remote regions underscores the necessity for resilient alternative energy systems. This study evaluates the efficiency and performance of a hybrid off-grid system integrating a solar photovoltaic panel with six thermoelectric generators (TEGs). Over a five-day experimental period, voltage, current, and power outputs were measured under load conditions ranging from 10 W to 50 W. The results indicate that a 12 V 8 Ah (96 Wh) battery maintains a 10 W load for approximately 9.6 hours. The hybrid configuration generated a total output of 19–21 V and 120–130 W, with the solar panel contributing 70% and the TEGs providing 30% of the total power. The system demonstrated voltage stability and a complementary operational synergy, ensuring a continuous energy supply during periods of low solar irradiance. These findings validate the solar–TEG hybrid system as a reliable and efficient renewable energy solution for off-grid applications.

1. INTRODUCTION

The demand for environmentally friendly electrical energy continues to increase, especially in remote areas that are not yet connected to the main electricity grid. Solar panels are an important solution due to their great potential for use as a source of electrical energy in rural regions[1]. However, the efficiency of solar panels is often limited because not all radiant energy can be converted into electricity—most of it becomes residual heat, which if not managed properly, reduces the performance and lifetime of the panel itself [2][3]. Therefore, effective heat management not only prevents performance degradation but can also open opportunities to recover this "waste heat" as an additional energy source.

To address this limitation, a Thermoelectric Generator (TEG) can be integrated with solar panels to utilize the temperature difference (thermal gradient) formed between the hot surface of the panel and the cooler ambient environment. TEG works based on the Seebeck effect, which directly converts this temperature difference into electrical energy. Thus, when combined with photovoltaic (PV) panels, the TEG acts as a complementary subsystem that converts unused thermal energy into additional electrical power. This integration helps improve overall system efficiency and ensures that energy generation continues even when sunlight intensity decreases, such as in cloudy or evening conditions.

The increasing global demand for clean and sustainable energy sources continues to drive innovation, particularly in rural and isolated areas that remain disconnected from the main power grid. Among various renewable options, solar photovoltaic (PV) technology has gained widespread attention due to its accessibility, simplicity, and environmental benefits. However, despite its advantages, the performance of solar panels is strongly affected by environmental factors—especially temperature. When solar irradiance increases, part of the absorbed energy is converted into heat rather than electricity, leading to a rise in panel temperature that can significantly reduce conversion efficiency. Several studies have shown that inadequate heat management on PV modules directly results in lower output performance and long-term degradation.

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To overcome this challenge, researchers have explored the integration of Thermoelectric Generators (TEG) with PV systems. A TEG can harvest the temperature difference between the hot and cold sides of a surface, converting waste heat into additional electrical power. When applied beneath solar panels, TEGs not only utilize excess thermal energy but also help moderate panel temperature, improving overall system efficiency. In this hybrid configuration, the PV acts as the main source of electricity during daylight, while the TEG provides a complementary supply derived from residual heat or when solar intensity drops, thereby ensuring energy continuity and system stability for off-grid use.

A number of prior studies have investigated PV–TEG hybrid systems from different perspectives. Fadrurrahman et al. [4] introduced a conceptual hybrid model but did not evaluate performance under fluctuating irradiance and load conditions. Bayusari et al. [5] focused on improving heat transfer using a copper plate on the TEG's hot side, achieving better thermal gradients but lacking analysis of long-term stability. Grace Clarissa Aurelia [6] examined transparent hybrid panels for BIPV applications and found improved cooling effects, yet the actual energy contribution from the TEG remained minimal. Similarly, Rifky & Nofendri [7] and Hayani et al. [8] tested series-parallel TEG arrangements, but their studies were limited in scope and duration, providing only partial insights into system reliability in real outdoor settings.

Although these studies confirm that combining solar panels and TEGs can enhance overall efficiency, most of them remain restricted to simulation or laboratory-scale experiments. The precise contribution of TEGs to hybrid energy output and their ability to maintain voltage stability during variable sunlight conditions have not been sufficiently analyzed. Consequently, this research aims to fill that gap by conducting an experimental evaluation of a hybrid off-grid power system that integrates a solar panel with six TEG modules. The investigation focuses on determining the proportion of power generated by each source, examining voltage stability, and assessing the feasibility of this hybrid configuration as a reliable and sustainable solution for low-to-medium power demands in remote areas.

2. RESEARCH METHOD

The methodology in this study used an experimental design[2]. The purpose of this experiment was to test seawater and freshwater cooling on solar panels and determine the input voltage, current, and surface temperature[3]. Figure 1 shows the flow chart of this study. The location used as the object of this study was the Leuwigede village hall field.

2.1 Data Collection Techniques

The research method used in this study was an experimental method with a system design and implementation approach. This study aimed to design and develop an off-grid hybrid solar panel and thermoelectric generator system and evaluate the effectiveness of solar panels in generating power based on the incoming current and voltage data. In addition, the data obtained was analyzed using the power triangle formula to obtain more accurate calculation results.

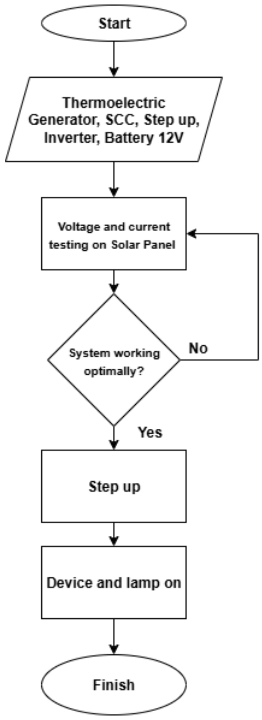

Fig. 1. Research Flow Chart

3. RESULTS AND DISCUSSION

The testing was conducted over ten days, from August 20 to 30, 2025, from 9:00 a.m. to 4:00 p.m. Western Indonesian Time in the front yard of a house in Leuwigede Village. Data collection was carried out in two stages: testing of solar panels and TEG without step-up, followed by testing of TEG with step-up and testing of the combined hybrid system. From August 20 to 25, the solar panels and TEG were tested without a step-up using two solar charge controllers. Subsequently, from August 26 to 30, testing of the TEG with a step-up and testing of the hybrid system were conducted. Test results were recorded every hour. The following are the results of the testing.

In the system, the step-up converter is used to boost voltage from the source to the load or inverter. Its efficiency was not measured, although the converter is not perfect and experiences power losses. Without measuring or estimating efficiency, the system analysis remains incomplete, as potential losses are not accounted for, which can affect battery capacity, TEG performance, and total system output.

Although the overall experimental period lasted ten days (August 20–30, 2025), only the data from five representative days were analyzed in detail. The first five days (August 20–25) were allocated for baseline measurements of solar panels and TEGs without the use of a step-up converter. These trials served to observe raw voltage and temperature responses under natural variations of irradiance. The remaining five days (August 26–30) were dedicated to testing the TEGs with a step-up converter and to hybrid system operation. However, due to data redundancy and similar performance patterns across those days, the results were averaged and summarized over a five-day dataset to ensure concise yet representative presentation. This approach allowed for clearer analysis without compromising the accuracy of the experimental findings.

3.1 System Design

As shown in Fig. 2, the system design adopts a tilted panel structure supported by a mild-steel frame with front and rear legs of different heights to achieve optimal sun exposure. The inclination angle improves daily irradiance capture while ensuring natural air circulation underneath the panel, which aids in maintaining lower operating temperatures. This mechanical setup also facilitates the placement of six TEG modules beneath the panel's backside, maximizing the thermal gradient between the panel's hot surface and the ambient air. The design demonstrates a practical approach for combining structural stability with thermal harvesting efficiency in small-scale off-grid systems.

Fig. 2. System design

3.2 Wiring design

Fig. 3 illustrates the complete wiring configuration of the hybrid system. Each of the six TEG modules is connected to a step-up converter before merging with the solar panel output, ensuring voltage compatibility and maximizing the contribution of the thermoelectric modules. The use of a Solar Charge Controller (SCC) between the power sources and the battery plays a critical role in regulating current flow, preventing overcharging, and maintaining a stable DC bus. The layered protection using both DC and AC MCBs enhances safety, particularly when alternating between charging and discharging cycles through the inverter. This integrated wiring scheme reflects an efficient and safe method for synchronizing two energy sources with differing voltage characteristics.

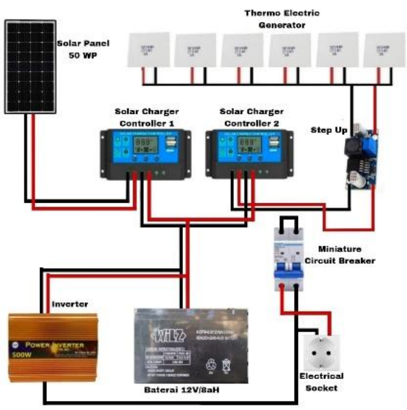

Fig. 3. Wiring design

3.3 Solar panel voltage data every hour

Solar panel voltage test results from August 20 to 25 in Table 1.

Table 1. Solar panel voltage data

NO	Time	Voltage (V)				
		Day 1	Day 2	Day 3	Day 4	Day 5
1	09.00	12.16	15.12	13.52	14.32	12.4
2	10.00	13.04	15.67	13.08	14.48	12.52
3	11.00	13.11	14.09	13.07	14.9	12.1
4	12.00	15.18	14.46	13.84	12.62	12.69
5	13.00	15.83	15.93	14.77	12.8	12.5
6	14.00	14.52	13.09	14.84	13.35	14.84
7	15.00	13.55	13.18	12.98	13.9	13.7
8	16.00	12.02	12.17	12.1	13.67	12.1
	Average	13.68	14.21	13.53	13.76	12.86

The voltage graph in Fig. 4 reveals a consistent daytime fluctuation pattern typical of PV modules under varying irradiance. Voltage peaks around midday (12:00–13:00) coincide with maximum solar radiation, while minor dips occur in the morning and late afternoon due to lower light intensity. The relatively narrow range of variation (12–15 V) across all test days indicates that the solar panel maintained stable performance under clear-sky conditions, confirming reliable operation of the panel and controller setup. This stability is essential for hybrid integration, as it provides a predictable baseline for TEG energy addition.

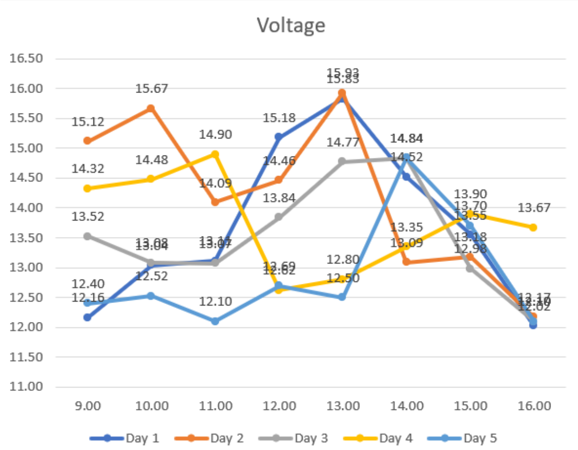

Fig. 4. Solar Panel Voltage Chart Graph

3.4 Thermoelectric voltage data without step-up every hour

The results of testing 6 thermoelectric voltages connected without step-up from August 20 to 25, 2025 are shown in Table 2.

Based on Table 2, the average thermoelectric voltage value is obtained by adding up all the hourly measurement results and dividing them by the number of available data points. From these calculations, the average daily voltage of TEG without a voltage amplifier was obtained, namely 0.2 V on the first day, 0.18 V on the second day, 0.21 V on the third day, 0.38 V on the fourth day, and 0.24 V on the fifth day. When averaged over the five days of testing, the voltage produced reached 0.24 V. In addition, Gaguk Marausna reported that in the use of TEG to utilize waste heat, the average voltage decreases as the temperature difference decreases because cooling the cold side is difficult to maintain[4].

Table 2. Thermoelectric voltage data without step-up

NO	Time	Voltage (V)				
		Day 1	Day 2	Day 3	Day 4	Day 5
1	09.00	0.18	0.2	0.19	0.16	0.15
2	10.00	0.16	0.22	0.17	0.18	0.2
3	11.00	0.18	0.18	0.18	0.21	0.24
4	12.00	0.22	0.26	0.23	0.19	0.29
5	13.00	0.26	0.17	0.25	0.24	0.34
6	14.00	0.25	0.15	0.29	0.19	0.28
7	15.00	0.19	0.14	0.21	0.16	0.25
8	16.00	0.17	0.14	0.18	0.13	0.2
Average		0.2	0.18	0.21	0.18	0.24

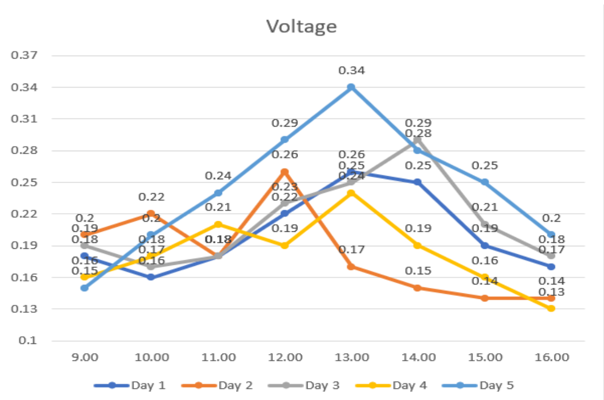

Fig. 4. Thermoelectric generator Voltage without step-up Graph

3.5 Thermoelectric voltage data using step-up every hour

The results of testing the voltage of 6 thermoelectric devices connected in series using a step-up from August 26 to 30,2025 are shown in Table 3.

Based on Table 3, the average voltage value on the Thermoelectric is calculated by adding up all the voltage measurements every hour, then dividing it by the amount of data obtained. From these calculations, the average daily voltage of the thermoelectric using step-up is obtained. On

In this test, conducted under clear weather conditions, step-up significantly increased the output voltage of the TEG modules, as shown in Figure 5. Without voltage increase, each module only produced 0.2–0.3 V, but after being connected in series and through step-up conversion, the combined output reached an average of 6.3–6.5 V. This increase indicates that the converter effectively optimizes the low voltage signal characteristic of TEGs into a usable voltage range compatible with PV systems. In addition, the stable pattern during the test day indicates good thermal coupling between the solar panels and the TEG modules, validating the feasibility of direct heat recovery into electricity.

Table 3. Thermoelectric voltage data using step-up

NO	Time	Voltage (V)				
		Day 1	Day 2	Day 3	Day 4	Day 5
1	09.00	6.11	6.23	6.12	6.17	6.14
2	10.00	6.24	6.27	6.2	6.18	6.22
3	11.00	6.37	6.4	6.27	6.65	6.23
4	12.00	6.66	6.41	6.25	6.63	6.23
5	13.00	6.69	6.4	6.34	6.66	6.21
6	14.00	6.58	6.52	6.31	6.59	6.2
7	15.00	6.53	6.48	6.29	6.62	6.23
8	16.00	6.48	6.33	6.25	6.54	6.19
Average		6.46	6.38	6.25	6.5	6.21

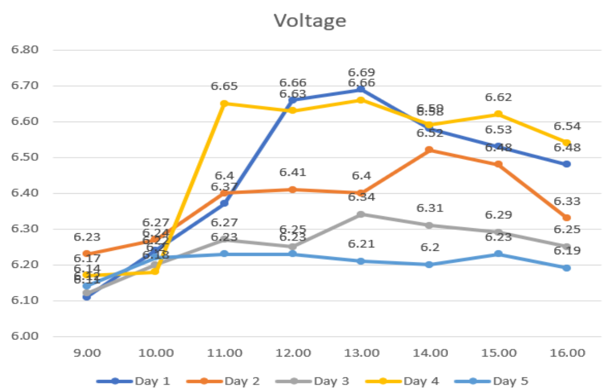

Fig. 4. Thermoelectric voltage data using step-up Graph

3.6 Combined (hybrid) average voltage data for 5 days in every 1 hour

The results of testing the voltage of the panel and 6 thermoelectric devices connected in series using a step-up from August 26 to 30, 2025 are shown in Table 4.

The hybrid voltage curve (Fig. 6) shows that integrating six TEG modules increased the overall system voltage from approximately 13–14 V (PV only) to 19–21 V in hybrid mode. This 30–35% increase confirms that TEGs contributed significantly to total energy generation. More importantly, the voltage curve exhibits reduced fluctuation compared to the PV-only setup, indicating that the hybrid configuration enhances voltage stability by supplementing energy during low-irradiance periods. Such stability is crucial for maintaining battery charging efficiency and preventing deep discharge during intermittent sunlight, especially in off-grid systems.

Table 4. The voltage data from the panel and 6 thermoelectric devices are connected in series using a step-up converter.

No	Day	Voltage (V)		
		Panel	TEG	Hybrid
1	One	13.68	6.57	20.25
2	Two	14.21	6.28	20.49
3	Three	14.58	6.35	20,93
4	Four	13.76	6.51	20,27
5	Five	13.13	6.21	19.34

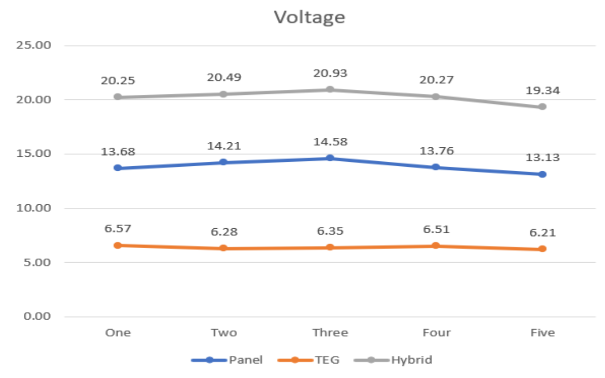

Fig. 5. Combined Voltage Graph (Hybrid)

Based on Figure 4.7, the average hybrid voltage value is calculated by adding up all the daily voltage measurements and then dividing them by the number of data points obtained. From these calculations, the combined (hybrid) daily average voltage is obtained. When averaged, the total voltage obtained by the hybrid system is 19.97V.

3.7 Analysis of Combined Voltage Test Results (Hybrid)

At night, a load test was conducted using a single 10W spotlight. A 12V battery with a current of 8Ah was used. From this data, the power generated by the battery can be calculated.

From the above calculation, we can see that the battery has a power of 96 watts. Calculate the load current of the lamp using a 10W lamp. From this data, we can find the current generated by the lamp by calculating the power of the lamp divided by the voltage of the battery.

From the above calculation, we know that the current generated by the lamp is 0.83 amperes. We can then determine how long the lamp can stay on with a load of 10W.

The above power and operation time calculations were carried out under several simplifying assumptions. The current (I) was assumed constant during the test, as the load was resistive and stable at 12 V DC. The 12 V 8 Ah battery was considered to be in healthy condition and fully charged before each cycle, and factors such as self-discharge, internal resistance increase, or aging effects were not included. Additionally, power losses from inverter conversion, wiring, and controller inefficiencies were neglected to focus solely on the proportional energy contribution of the solar panel and TEG modules. Therefore, the resulting power and duration values represent ideal theoretical estimates; real-world performance may be slightly lower due to unavoidable system losses.

In the lamp load experiment, testing was conducted using one 10W lamp and two 20W lamps. Based on calculations, the 10W lamp can stay on for approximately 9.6 hours. However, when the load was increased, the operating time became shorter. When the 10W lamp was combined with one 20W lamp (total power 30W), the system could only stay on for 3.2 hours. Then, when another 20W lamp was added (total power 50W), the lighting time dropped to approximately 1.92 hours. From these results, it can be seen that without energy supply from sunlight, the duration of lighting is greatly affected by the load used. This is in line with the research by Amin., which states that an increase in lamp power causes a significant decrease in the release of electrical energy from the battery[5]. Similar findings were also reported by Suprianto, that the greater the total lamp power used, the shorter the operating time of the solar power system due to increased energy consumption[6].

While the analysis of battery capacity provides an overview of short-term load sustainability, the study did not extend to examining the charging–discharging behavior or long-term performance of the battery. In renewable energy systems, battery health and efficiency can degrade over repeated cycles due to temperature fluctuations, depth of discharge, and charge rate irregularities. These factors influence both the usable capacity and the lifespan of the storage unit. Future work should include continuous monitoring of the battery's state of charge (SoC), charging efficiency, and cycle degradation to better understand the interaction between hybrid power generation and energy storage. Such analysis would provide a more comprehensive view of the system's reliability and sustainability in real off-grid applications.

3.8 Analysis of Hybrid System Test Results

This analysis was conducted to determine the percentage of solar panel usage and to ensure that the tested system could truly operate at maximum capacity. Conclusions were drawn from a summary of calculations made during the testing process. The percentage value was then calculated using the power triangle formula.

- Day One

On the first day, data was obtained with an average voltage of 20.25 V and a current of 6.2 A. From these values, the power generated can be calculated as follows:

On the first day, the power generated reached 125.55 W. This value was then calculated to determine the percentage of utilization of solar panels and thermoelectric panels.

The first step in calculating the Power Contribution from the Panel and TEG is to use the formula:

Test results show that the solar panel produces a voltage of 13.68 V, while the TEG produces 6.57 V. When combined, the hybrid voltage reaches 20.25 V with a total power of 125.55 W. Based on current calculations, the system draws a current of approximately 6.20 A. The power contribution is divided into approximately 84.82 W from the solar panel and 40.73 W from the TEG, bringing the total in line with the system's output power. In percentage terms, the solar panel contributes approximately 67.56%, while the TEG contributes approximately 32.44%. These results indicate that both energy sources work well together in supporting the system's power output. These findings support Fathana Salsa Hayani's research, which reports that a hybrid thermoelectric-thin film solar panel system can generate significant daily electrical energy from the temperature difference in solar radiation [7]

- Day Two

On the second day, data was obtained with an average voltage of 20.49 V and a current of 6.2 A. From these values, the power generated can be calculated as follows:

On the second day, the power generated reached 127.03 W. This value was then calculated to determine the percentage of utilization of solar panels and thermoelectric panels using the following formula:

Test results show that the solar panel generates a voltage of 14.21 V and the TEG generates 6.28 V. When these two sources are combined, the hybrid voltage reaches 20.49 V with a total power of 127.03 W. From the calculations, the current flowing in the system is approximately 6.20 A. The solar panel contributes approximately 88.10 W of power, while the TEG contributes approximately 38.94 W. In percentage terms, the panel contributes approximately 69.34% of the total power, while the TEG contributes approximately 30.66%. These results show that both energy sources work together and provide a stable power supply to generate the total output of the system.

- Day Three

On the third day, data was obtained with an average voltage of 20.93 V and a current of 6.2 A.

On the third day, the power generated reached 129.76 W. This value was then calculated to determine the percentage of utilization of solar panels and thermoelectric panels using the following formula:

Test results show that the solar panel produces a voltage of 14.58 V and the TEG produces 6.35 V. When combined, the two produce a hybrid voltage of 20.93 V with a total power of 129.76 W. From these values, the current flowing through the system is approximately 6.20 A. The power contribution is divided into approximately 90.40 W from the solar panel and 39.37 W from the TEG. In percentage terms, the panel contributes approximately 69.65% of the total power, while the TEG contributes approximately 30.35%. These results indicate that the two energy sources complement each other and are able to work stably in supporting the system's power output.

- Day Four

On the fourth day, data was obtained with an average voltage of 20.27 V and a current of 6.19 A. From these values, the power generated can be calculated as follows:

On the fourth day, the power generated reached 125.41 W. This value was then calculated to determine the percentage of utilization of solar panels and thermoelectric panels using the following formula:

Test results show that the solar panel produces a voltage of 13.76 V and the TEG produces 6.51 V. When combined, the two produce a hybrid voltage of 20.27 V with a total power of 125.41 W. From these values, the current flowing through the system is approximately 6.19 A. The power contribution is divided into approximately 85.13 W from the solar panel and 40.3 W from the TEG. In percentage terms, the panel contributes approximately 67.88% of the total power, while the TEG contributes approximately 31.40%. These results indicate that the two energy sources complement each other and are capable of working stably to support the system's power output.

- Day Five

On the fifth day, data was obtained with an average voltage of 19.34 V and a current of 6.2 A. On the fifth day, the power generated reached 125.41 W. This value was then calculated to determine the percentage of utilization of solar panels and thermoelectric panels using the following formula:

In this test, the hybrid system generated a voltage of 19.34 V with a total power of 119.9 W. From the calculations, the current flowing in the system was around 6.20 A. The solar panel contributed around 81.4 W or 67.88% of the power, while the TEG contributed around 38.5 W or 32.11%. These results indicate that the panels remain the primary source, but the TEG still provides a significant amount of additional energy, ensuring that the total system power remains optimal.

Overall, the graphical and tabular analyses highlight that TEG modules not only enhance total power output but also improve system reliability through voltage stabilization. The results demonstrate that hybridization effectively mitigates the inherent intermittency of solar energy. This finding aligns with prior studies emphasizing the role of thermoelectric integration in improving renewable energy utilization efficiency. However, further optimization in thermal interface materials and cooling strategies could increase the conversion efficiency of TEGs in future prototypes.

4. Conclusion

Test results show that hybrid solar panels and six TEG systems can operate stably. A 12V 8Ah battery with a capacity of 96 Wh can power a 10W lamp for approximately 9.6 hours, and this duration will decrease if the load is increased. During ten days of testing, five days of combined voltage testing in sunny weather conditions using an upgraded TEG was in the range of 19–21 V with a power of approximately 120–130 W, where the solar panel contributed about 67–70% and the TEG added about 30%, proving that the use of a voltage booster is more effective and beneficial. The combination of these two technologies makes the power supply more stable and sufficient for light to medium loads. For further development, this system can still be improved by improving TEG heat management, using larger batteries, adding monitoring devices, trying other load variations, adjusting the panel position more precisely, and considering additional energy sources.

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