

Design and Research of Thermoelectric Energy Harvesting Methods for Instantaneous Use

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Abstract

In today's consumer-oriented market, researchers are attempting to harness energy from ambient sources for sustainable energy generation, leading to a reduction in dependency on conventional energy sources. Energy harvesting methods offer enormous opportunities to derive energy from our natural surroundings to directly operate self-powered devices or store it for later use. Generating energy from our nearby environment seems to be a promising solution to address the growing concerns of powering small devices and sensors. Energy harvesters are similar to transducers, designed to extract energy from sources available in the environment and convert it into usable electrical energy. This research aims to show the practical implementation of triboelectric and thermoelectric energy harvesting using hardware prototypes and setup. A usable amount of energy is extracted from an energy harvester, and results are validated using a hardware model for real-time applications. In addition, the study focuses on analyzing the working principles, design considerations, and performance characteristics of both triboelectric and thermoelectric energy harvesting systems under different operating conditions. The proposed experimental setup evaluates the efficiency, output voltage, and power generation capability of the developed prototypes, highlighting their suitability for low-power electronic applications. Emphasis is placed on demonstrating the reliability and feasibility of these energy harvesting techniques for powering sensors, wearable electronics, and Internet of Things (IoT) devices. The results obtained from the experimental investigation indicate that ambient energy harvesting can serve as a viable supplementary power source, contributing to sustainable and eco-friendly energy solutions. This work further provides insights into the potential integration of hybrid energy harvesting systems to enhance overall energy output and ensure continuous power availability for autonomous and self-powered systems.

Keywords: Thermoelectric generator, Peltier module, thermoelectric generator modules (TEG) modules, thermal conductivity, Peltier cells

INTRODUCTION

The generation of electrical energy from heat stores huge potential owing to the availability of heat energy in various forms, such as waste heat from engines, domestic applications, and industrial operations. The largest source of heat energy is the abundant sunlight falling on the Earth's surface.

Therefore, thermal energy conversion practices are a favorable area of research and exploration. The phenomenon of thermal to electric energy conversion rests on the Seebeck effect. The Seebeck effect was discovered by Thomas Johann Seebeck, who reported the production of voltage when two materials with different compositions were subjected to a temperature difference at their junction. The thermal gradient effect in certain materials causes the diffusion of charge concentration owing to the flow of heat energy generated by the electromagnetic force. Devices can operate on this effect to generate thermoelectric

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energy if a sufficient temperature gradient is maintained. A constant supply of heat flow can generate the corresponding electrical energy if a sufficient amount of heat is rejected to maintain the temperature gradient. A large temperature gradient with a constant value is desirable for greater energy generation (Figure 1).

The past decade recorded a rapid development and deployment of compact, low-power smart electronic devices called sensor nodes forming wireless sensor networks. These sensors deployed for monitoring and data acquisition networks consist of many sensor nodes for processing but with limited battery capacity. As the location of deployment of these devices is often difficult to access for human beings, providing a continuous power supply is a challenging job [1]. Also, with the advancement of technology, these devices are interconnected not in particular geographical areas but across different countries. Advanced networking technologies like the Internet of Things are a very good example of such interconnected devices. Looking at the enormous number of devices or sensor nodes connected in such applications, their power needs increase manifold. Along with a larger amount of power, these devices demand an uninterrupted supply of power for reliable and unambiguous results [2–5]. Currently, they are powered using batteries of different ratings and sizes depending on the type of application. A battery provides a stable power source, and for low-power devices, may last for a longer duration. But the replacement of these power sources in case of complete discharge is not easy. Due to inaccessible locations, replacement becomes costly and takes longer time. This increases the overall system cost and decreases the system reliability. This motivated researchers worldwide to search for some alternate sources which could fulfill the power requirement of such devices. The devices and sensors discussed above are often low-powered and consume a very small amount of power for operation.

A detailed review of waste heat recovery highlighted for existing technologies and future potential applications is discussed. Recent advancements have seen the use of solar energy to improve the performance of TEGs. Electrical power generation from thermoelectric devices using thermal energy from sunlight attracted researchers worldwide [6]. These systems have three basic components: a heat-collecting surface, a thermoelectric module, and a heat sink for generating an optimum temperature gradient. The incident heat flux from solar energy can be concentrated on the hot side of the thermoelectric module. Non-concentrating mechanisms have also existed with good electrical power levels. Solar thermoelectric generators, referred to as Solar Thermoelectric Generator (STEG), can use almost the entire spectrum of sunlight as compared to Photovoltaic (PV) designed for a fraction of the spectrum. This may result in higher energy conversion capability for these systems. Early investigations into STEG reported a very low conversion efficiency of about 0.63%, primarily due to the lack of suitable thermoelectric materials. A comparative performance analysis of parabolic and flat-plate collector-based STEG systems for power generation was reported in 2005. The actual model was designed and studied in software using a coding-based Thermoelectric Module (TE) module component [7–10]. Two STEG models were presented, one using a heater for heating and another dependent on reflected sunlight from aluminum foil. This helped in the study of feasibility for developing such models for future investigations. A solar-based thermoelectric generator was developed using a flat-panel configuration to achieve high thermal energy concentration, resulting in a comparatively higher efficiency of 4.6%. A vacuum enclosure was used to increase the heat absorption. This work presented the potential of using sunlight without a complex concentration mechanism deployed for STEG electricity generation systems. Such systems are good candidates for large-scale electricity generation by rooftop deployment of thermoelectric generators [8]. The feasibility of producing small-scale power from a cleaner energy source such as solar energy was successfully demonstrated. The thermal energy crossing the PV module is harvested by distributing the gathered energy onto a thermoelectric module. The heat energy was transferred to the TE module using a metal sheet, and natural ambient air flowing in the vicinity was used for cooling the opposite side. This cost-efficient system produced an output voltage of 2.5 V, which is enough to power low-power devices. This work also revealed the fact that certain metal sheets, when integrated with the hot-side surface of the TEG module, can enhance the heat absorption capability [9].

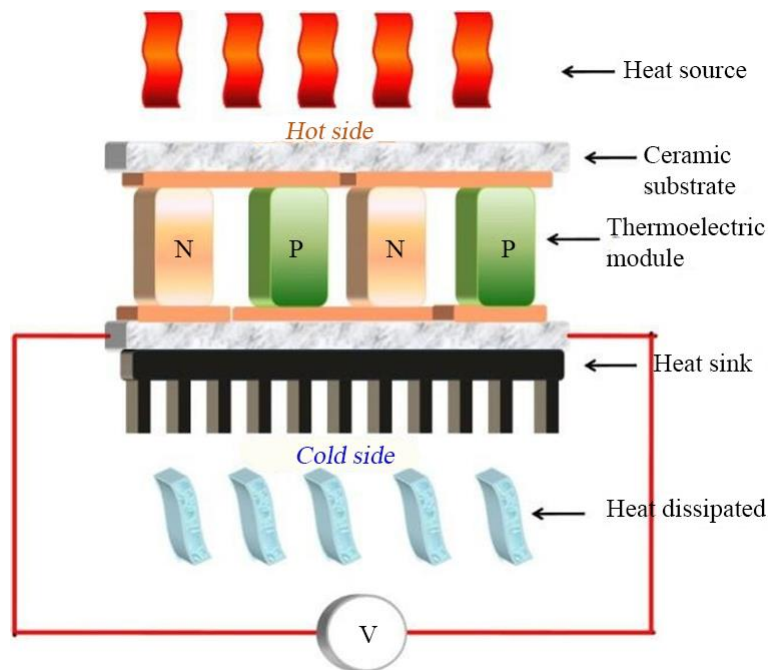


Figure 1. Schematic of thermoelectric generator model.

The efficiency of energy conversion by a thermoelectric generator is expressed by the property of the material, ZT , known as the figure of merit.

The work presented here was carried out to examine the effect on output voltage due to improved heat absorption by the thermoelectric surface when connected to a metal surface. In the literature review presented above, it was reported that heat distribution by a metallic surface resulted in increased energy conversion efficiency. A study was conducted to select a metal for maximum output voltage from thermoelectric energy generation from selected conducting materials. The performance analysis was carried out for different material sheets configured to a thermal module for allocating maximum possible heat energy for open-circuit voltage generation. A commercially available module, a Peltier cell working on the principles of thermoelectricity, is used as a thermoelectric power generation device. Initially, two materials, aluminum (AL) and iron (Fe), were selected due to their good heat transfer capability. A comparative study for Al and Fe metal sheets was done to select the better material for continuous heat absorption from sunlight. For further investigation, aluminum and iron sheets with black paint coating were integrated with the system under test to examine any improvement in output power levels. A black surface is known to absorb all the incident sunlight and can capture the maximum amount of heat energy. This directly increases the heat absorption capacity [10–15].

SYSTEM DESIGN

The experiment was first carried out using a single module, and then three modules were connected in series to increase the output voltage. To produce an output voltage from the selected Peltier cells, a constant temperature difference should be maintained between the two opposite sides of the cell. For the experimental setup, Peltier modules of the TEC1-12706 were procured from the local market. Each module was 40 mm × 40 mm wide and 3.9 mm thick and was used in the Seebeck mode for power generation. The thermocouple material used in these modules was Bi_2Te_3 (bismuth telluride) with an operating temperature of up to 200°C. A total of 127 thermocouples were fabricated inside each module, which were connected in series electrically and sandwiched between two ceramic plates for mechanical strength. To generate a higher temperature gradient between the two opposite sides of the thermoelectric modules, one side is exposed to a heating source, while the other is cooled simultaneously using a heat sink mechanism. A heat sink with equally spaced aluminum fins for maximum heat dissipation was integrated to cool the surface [16]. The cold side of the module also tends to become hotter with time

owing to heat transfer; therefore, an active arrangement for continuous heat release is required. For continuous cooling, an aluminum heat sink connected to a Central Processing Unit (CPU) fan was deployed to cool one side of the surface. To eliminate the chances of developing air gaps between the ceramic surface of the module and the aluminum heat sink, a thermal interfacing material can be used. In this study, we used thermal grease to attach a heat sink to a thermoelectric module for better heat transfer. This allows maximum heat conduction, as thermal grease is known to have high thermal conductivity. To further maximize the quantity of heat dissipated by the system, a CPU fan was used beneath the heat sink. The other side was exposed to a continuous heating source to receive the heat energy required for heating. Ambient solar energy, which is easily available, was used to heat the other side of the module here [17–20].

EXPERIMENTAL WORK

First, the module was put directly in an open area for unobstructed sunlight incidence on the hotter side. This generated a very low output voltage when recorded for an open-circuit configuration. Next, the process was repeated to investigate the performance of chosen materials on the amount of heat transferred. A flat aluminum sheet was attached to the hotter side using thermal grease. Aluminum was chosen owing to easy availability, high thermal conductivity, and low-cost. Other materials with better heat conduction are gold and copper, but their cost is much higher than aluminum. Table 1 lists the thermal conductivity of some materials like iron, copper, etc. Another good candidate for good heat conduction is iron (Fe), which is again a low-cost metal. A thin sheet of iron was also selected to test and analyze the effect on the amount of heat absorbed as compared to an aluminum sheet. The energy from the sun was incident directly on aluminum and iron sheets when placed over the TEG surface, and the corresponding open-circuit voltages were recorded with respect to time. The same process was repeated for black paint by applying a single coat of paint onto aluminum and iron sheets. The paint used in this study was black paint with a matte finish, again procured from the local market. A DC voltage generated from a thermoelectric generator was recorded for all the configurations for 60 seconds using a measuring instrument [21–30]. A Fluke multimeter was used to store the voltage readings at uniform intervals of one second. The data were stored and used to plot the DC voltage graphs for all the materials under test [31–35].

In the initial comparative analysis between aluminum and iron sheets, it was recorded that the aluminum sheet delivered higher output voltage as compared to the iron sheet. As the thermal conductivity of aluminum is higher, better heat transfer was achieved using aluminum. When the heat is evenly distributed over large sheets was able to heat the thermoelectric module. This resulted in the development of a higher temperature gradient between the two surfaces of the thermal modules. The heat sink, on the other hand, was able to dissipate the heat from the other side continuously to generate a constant temperature difference. The use of thermal grease helped in better power generation due to better thermal connection between the source and device. When the sheets were directly connected to the surface, the voltage levels were less as compared to sheets connected with thermal grease to the module [36–40]. As the intermediate results revealed that higher voltage levels can be generated using aluminum sheets, further investigation was done with aluminum sheets only. For our next analysis, black metal paint was coated on the aluminum sheet to further augment the heat photographic density and generate higher output voltage. Due to the intrinsic property of the black surface, the coated aluminum sheet received a high amount of heat energy directly from sunlight. A further increase in open-circuit output voltage was observed. The experiment was repeated to validate the results and findings. Although the painted aluminum sheet attached to the TEG module delivered a significant amount of output voltage, it was desired to enhance the power levels further. Other high-cost materials may have delivered better output power, but owing to their high material cost, they could not be employed to enhance the voltage levels. Another possible combination is to cascade a number of modules to generate higher power. Using the previously designed mechanism, three such Peltier cells were combined to generate better results. These three modules were connected in series electrically to

add up the voltage levels generated by them individually. The modified configuration with three Peltier cells was again connected to black paint-coated aluminum sheets. Separate heat sink modules were connected with Peltier cells to achieve the required temperature gradient in all three modules. As recorded from the received voltage levels, the series-connected cells were able to generate a higher amount of voltage, which was sufficient to power a low-power device. A maximum voltage of 2.28 V was recorded for the series configuration, proving the potential to harness a substantial amount of electrical energy from a renewable energy source [41–44].

RESULTS AND DISCUSSION

A TEC1-12706 Peltier module-based thermoelectric generator system was designed and tested for maximizing the power output by increasing the amount of heat being absorbed. To increase the available thermal energy from the thermal source, a comparative analysis was done by attaching Al and Fe sheets on one side of the thermoelectric module. The readings presented here were recorded at 11:30 a.m. on 11th October 2025 at an average room temperature of 31°C in Delhi. Initially, the effect of placing a metal sheet on the power output of the thermoelectric module was tested. A visible increase in open-circuit output voltage was recorded when a metal sheet was connected to the TEG as compared to direct heating results. Figure 2 shows the open-circuit output DC voltages generated by heating the module directly under sunlight and heating through an Al sheet. It can be noted from the graph that the output voltage increased more than twice when an Al sheet was deployed for transferring the heat energy from sunlight evenly throughout the surface [45]. The output voltage increased gradually after engaging the complete setup in ambient sunlight. The open-circuit voltage was recorded for sixty seconds time duration. A number of samples of generated voltage were recorded at uniform intervals of one second each, and a total of sixty values were stored. The first usual set of readings was taken for heating effect by energy coming directly from sunlight in the absence of any heat-absorbing surface. To achieve this, the hot side of the TEG module was placed facing directly under sunlight. The direct application of heat energy from the sun yielded a maximum voltage of 0.24 V. A second set of readings was taken to visualize the effect of an aluminum sheet on the amount of open-circuit voltage recorded by the setup still placed under sunlight. An aluminum sheet, placed on the hot side of the system placed under sunlight, generated 0.48 V output voltage. A two-fold increase in output voltage was recorded using the same thermoelectric power generation system. It validated the potential of using metal sheets for enhancing the electrical output. Figure 2 gives the output voltage plot for open-circuit voltage generated using direct heating and heating using an aluminum sheet. After coating matte-finish black paint on the aluminum sheet, it was connected to the hot side of the module placed under sunlight [46–60].

Figure 3 shows the graphs of the output voltage for Al and Fe sheet heating. As evident from the figure, the output voltage with the Al sheet mounted on the Peltier cell is higher than that with the iron sheet.

Figure 4 shows the graph of output voltage using black paint. A noticeable change in output voltage is visible from the plotted results. The maximum recorded output voltage was 0.76 V, which is clearly higher than the aluminum sheet heating result and much higher than the voltage generated by direct heating [61–90]. It was desired to further increase the output voltage and reach an appreciable value of around 2 V. A normal battery cell available in the market is designed to deliver a stable 1.5 V voltage. For recharging such a battery, a voltage source should be able to generate an appropriate amount of output voltage. The above experiment was repeated for an array of three Peltier cells connected in series. Initially, an aluminum sheet was placed on top of every Peltier cell, and the complete setup was placed under sunlight. A large increase in output voltage was recorded for this configuration. While a single aluminum sheet-mounted Peltier module could generate 0.48 V output voltage, three such modules were able to deliver a 1.5 V output voltage. This results in a much higher voltage compared to the results from a single cell. When compared with the output generated using direct heating, the output voltage increased significantly using the array of three Peltier cells. This demonstrates an alternative approach to enhance the performance of the system under test [91–140].

Table 1. Thermal conductivity of different materials.

Material	Thermal conductivity ($\text{W m}^{-1}\text{K}^{-1}$)
Diamond	543
Silver	427
Copper	390
Gold	318
Aluminum	237
Iron	80

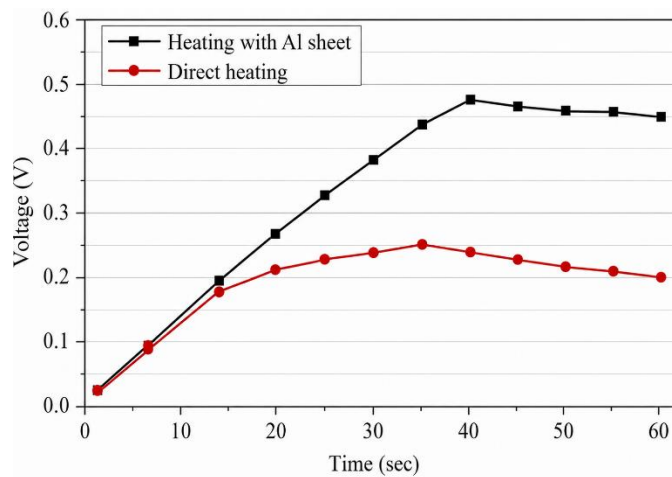
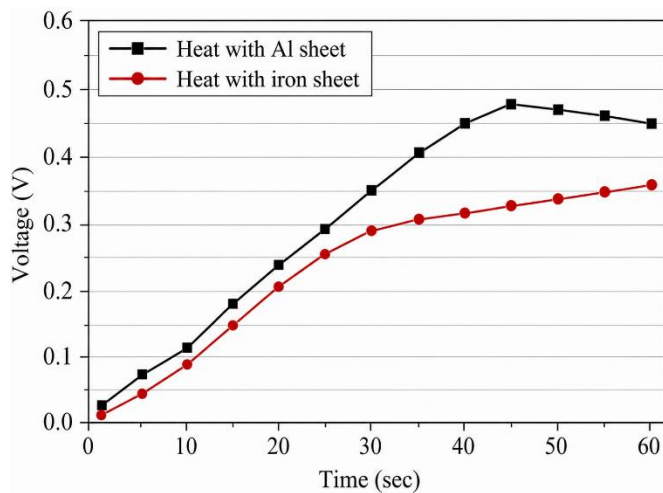
**Figure 2.** Output voltage for direct heat application and Al sheet on a single Peltier cell.**Figure 3.** Output voltage for Al and Fe sheets on a single Peltier cell.

Figure 5 shows the output voltage graph received from three Peltier cells as compared to the output voltage from a single cell when mounted with an aluminum sheet. The excellent results from three Peltier cells motivated further investigation using a black paint-coated aluminum sheet. The three cells placed under a heat energy source were connected to black paint-coated aluminum sheets. All three cells were mounted with painted sheets, and the combined voltage in series connection was recorded. This configuration resulted in a 2.28 V output voltage, which is an appreciable increase in device performance. When compared to aluminum sheet-mounted three cells, further enhancement in output voltage was recorded. When compared to a single Peltier cell with the same formation, which produced 0.78 V, an appreciable increase in open-circuit voltage was recorded. This demonstrated the capability of increasing electrical energy generation from designed thermoelectric generators. The final

arrangement of three Peltier cells with a black-painted surface elevated the output voltage from a lower value of 0.24 V to a substantial level of 2.28 V. This amounts to an overall 850% increase in output voltage. Figure 6 shows the output voltage graph for a paint-coated aluminum sheet using single and three modules. Figure 7 gives combined output voltage graphs for all the configurations discussed above. Clearly, an appreciable increase in the output voltage with a black-painted Al sheet mounted on the cell as compared to a direct heating cell is visible [141–149].

Although the output voltage increased for other configurations, the former case provided a voltage reading that can be further enhanced using an appropriate electrical circuit. These elevated voltage levels can be employed directly to operate low-power devices. The results presented above demonstrate the capability of harnessing low-power energy from a simple thermoelectric generator assembly. This study can help further investigate the approach of increasing device performance for thermoelectricity generation. These TEG modules can be integrated with solar systems for water heating on rooftops. This PV-TEG power co-generation system can generate a noticeable amount of energy using a single renewable energy source. At locations with ample sunlight availability, the output voltage from a simple Peltier module is sufficiently large to motivate further research for boosting this voltage. Even in places where maintaining a supply of heat energy from the sun is difficult, the availability of waste heat can be considered for heating the metal plates evenly.

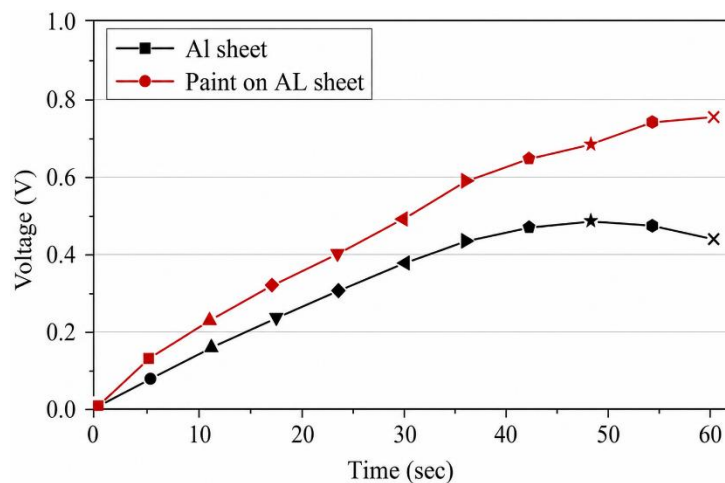


Figure 4. Output voltage for plain Al sheet and painted Al sheet on a single Peltier cell.

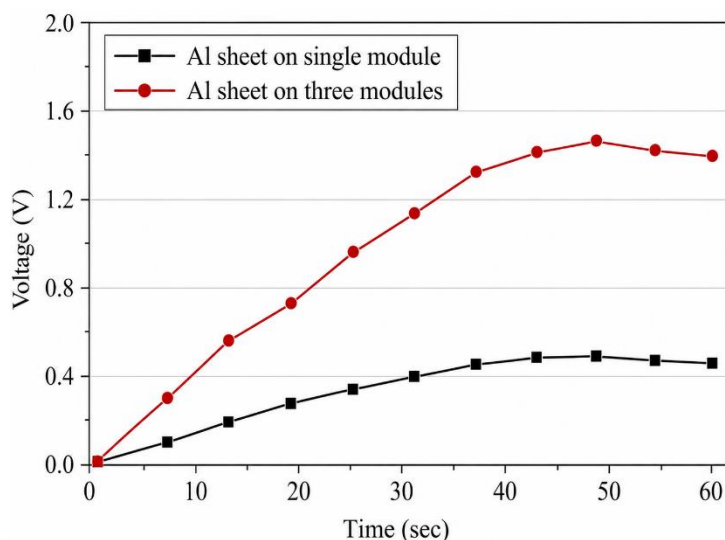


Figure 5. Output voltage from a single Peltier cell and three Peltier cells with mounted Al sheet.

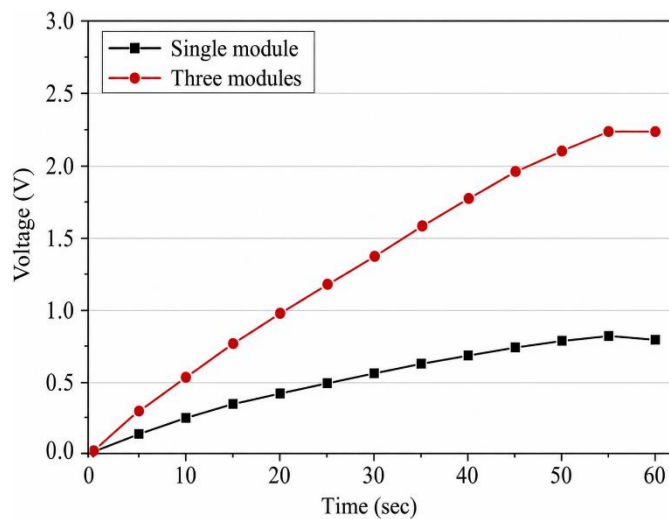


Figure 6. Output voltage from a paint-coated sheet on a single Peltier cell and three Peltier cells.

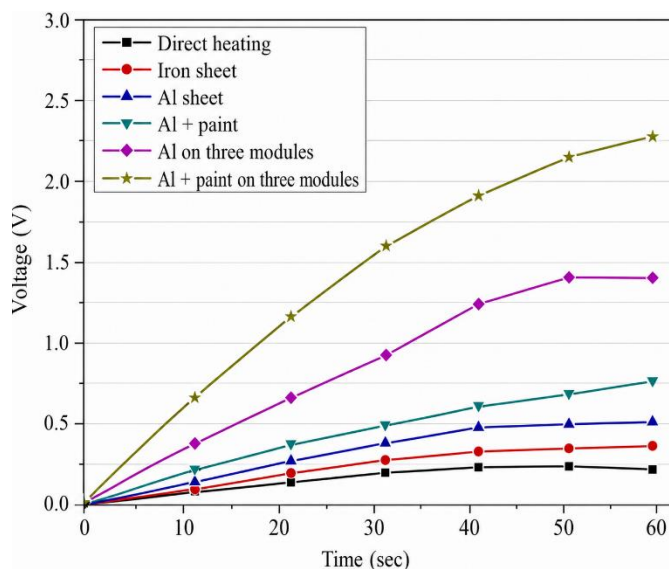


Figure 7. Open-circuit output voltage for all the materials

CONCLUSION

A simple thermoelectric generator was designed and tested to convert the heat energy received from sunlight into usable electric energy. Materials with better thermal conductivity were selected to enhance the performance of the designed system. An experimental investigation conducted by connecting a single commercial Peltier cell to an open-circuit recorded a 0.24 V output voltage. This cell generated 0.48 V when attached to an aluminum sheet for enhanced heating, while an iron sheet delivered 0.37 V. Further study revealed that a black paint-coated aluminum sheet improved the generated voltage to 0.76 V. To further increase the voltage, three such modules were connected in series, and an impressive output voltage of 2.28 V was recorded. Clearly, the three cascaded modules mounted on a black paint-coated aluminum sheet delivered the maximum output voltage. The attached aluminum sheet can provide additional protection to the thermoelectric module from physical wear and tear. The generated voltage is sufficient to provide the required electrical energy to micro/low-power devices. No special fabrication or material preparation processes were required for this experimental analysis. Although the overall size of the system increased compared to the single Peltier cell arrangement, an impressive increase in the output voltage was recorded with the black-absorbing surface. To reduce the number of cells required to generate a sufficient amount of output power, a study on the integration of voltage amplification circuits can be considered for future work.

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