

Development and Implementation of Solar–Thermoelectric Hybrid Energy Harvester

Anish Kumar^{1,*}, Praveen Kumar Choudhary²

Abstract

In today's consumer-oriented and technology-driven market, researchers are increasingly emphasizing the need to harvest energy from ambient and renewable sources to support sustainable power generation and to minimize dependence on conventional energy resources such as batteries and fossil-fuel-based electricity. The rising deployment of portable electronics, wireless sensor networks, and Internet of Things (IoT) devices has created an urgent demand for compact, low-power, long-life, and maintenance-free energy solutions. In many real-world scenarios, frequent battery replacement is impractical due to high cost, limited accessibility, and environmental concerns related to battery disposal. Hence, ambient energy harvesting has emerged as a promising approach for enabling self-powered electronic systems. Energy harvesting techniques provide enormous potential by converting naturally available energy such as human motion, mechanical vibrations, thermal gradients, airflow, and other waste energy into usable electrical output. Generally speaking, energy harvesters are transducers that take in energy from their surroundings and transform it into electrical power that may be stored or used directly. Among various harvesting mechanisms, triboelectric and thermoelectric energy harvesting methods are considered highly advantageous due to their simple structure, lightweight configuration, scalability, and suitability for small-scale applications. This research focuses on the practical implementation and performance validation of thermoelectric energy harvesting (THEH) using a developed hardware prototype and experimental test setup. A usable amount of electrical energy is generated under realistic operating conditions, and the output parameters are measured, analyzed, and validated to assess feasibility for real-time applications. The obtained results confirm that triboelectric and thermoelectric-based harvesting can be an effective solution for powering low-power electronics and self-sustaining sensing systems in future smart applications.

Keywords: DC–DC boost converter, generator system, thermoelectric generator (TEG) modules, thermocouple, solar thermoelectric generator (STEG)

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INTRODUCTION

Low-power electronic and portable devices always require a continuous power supply, which is usually fulfilled by batteries. To minimize the use of battery power supply for these devices, discovering new renewable energy sources has become a key area of research. These renewable energy harvesting methods are able to utilize the untapped surrounding ambient energy from the environment and can persuasively address the issues. Many techniques such as thermoelectricity, piezoelectricity, pyroelectricity, photovoltaic, triboelectricity, etc. are studied broadly to understand the capturing and efficient harnessing

of energy from these ambient sources. Another development for the maximum utilization of available energy sources is hybrid integrated systems. Many such techniques are available that combine two or more sources in a single integrated system for cogeneration. Among the listed technologies, a thermoelectric energy harvester/generator can capture spontaneously available thermal energy from sunrays, power plants, vehicles, and pavements to generate electrical energy by the Seebeck effect [1]. A semiconductor-based thermocouple can be employed to generate electrical energy from thermal energy provided a requisite temperature gradient is maintained constantly. These thermocouples are available in the form of commercially available modules with a ceramic outer covering. In the absence of any moving part for energy generation, these lightweight modules offer various advantages like noiselessness, robustness, and larger shelf-life. Various compositional and structural explorations for the fabrication of semiconductors with small band gaps have provided new and efficient thermocouple materials for further examination.

In the last few decades, researchers have shown greater interest in the efficient utilization of solar energy for electricity generation. Few attempts have been made to elevate the contributions of thermal energy in sunlight for harnessing usable energy, with some high-performance coatings for enhanced heat absorption. An ample amount of heat available from sunlight can easily operate the thermoelectric modules by creating a temperature difference/gradient required for corresponding thermal heat conversion. Association of solar–thermal effects together for power generation has seen plenty of promising applications like water heating, electricity generation, water distillation, etc. [2–4]. One study integrated carbon material with bismuth telluride modules using carbon nanotube–based composites featuring a nanostructured architecture, achieving approximately 1% output efficiency under ambient sunlight. Another work designed and analyzed a solar–thermoelectric generator (STEG) that delivered an output power of 0.91 W with a maximum attainable efficiency of 2.21% when operated within a vacuum enclosure.

A flat-panel type STEG was later demonstrated with a peak efficiency of 4.6%, which was further enhanced through the application of optical concentration techniques. In a separate development, a thermoelectric generator employing a polymethyl methacrylate (PMMA) Fresnel lens system for heat concentration achieved a reported efficiency of 51.33%, generating 1.08 W of power under matched load conditions at the output side.

Carbon nanotubes and graphene oxide are examples of zero band gap materials that can be employed to improve the performance of thermal-based energy harvesting methods. They increase the heat absorption capacity of the surface of the thermoelectric device to improve its performance. Candle soot with a high carbon content is a well-known cost-effective source for carbon nanoparticle fabrication. It displays superhydrophobic properties and provides stable results even at 500°C [5]. In the visible light spectrum, the deposition of candle soot on a surface exhibits favorable properties, such as luminescence [6]. When concentrated sunlight is directed onto highly absorbent materials, the output power generated increases significantly. One study reported a 50-fold enhancement in harvested energy using a candle-soot-coated lead zirconate titanate (PZT) pyroelectric device, while another demonstrated a 17-fold improvement through diesel exhaust soot coating. In a related approach, a carbon-based double-layer solar–thermal structure was proposed to localize heat effectively for steam generation.

For efficient thermoelectric generator (TEG) operation, maintaining an optimal temperature difference across the module and ensuring matched load impedance are essential. Maximum power transfer occurs when the load resistance is equal to the internal resistance of the TEG. To facilitate battery charging, one study connected three TEG modules to a microcontroller-controlled single-ended primary-inductor converter (SEPIC) DC–DC converter. Another study reported TEG arrays achieving 80% efficiency using buck–boost converters to improve load conductance. A maximum power point tracking (MPPT)–based TEG system with synchronous rectification was also developed, capable of transferring 47 W to a load. Additionally, a SEPIC converter was employed in a separate design to charge a Li-ion battery using a single TEG module.

A boosted voltage of 47.54 V across a 10F capacitor for a temperature difference of 56°C. In this study, we designed a cost-effective solution for substantial enhancement of thermoelectric energy harvesting. We exposed the upper surface of the thermoelectric module (TEC-12706) to a candle flame multiple times for better heat absorption by the blackbody. The required temperature difference was maintained using concentrated solar radiation and regular water flow to obtain better electrical output. The voltage was further increased using a DC–DC boost converter. To demonstrate the energy storage capability of the system, we also charged a 2.4 V VARTA NI-MH rechargeable battery from the generated amplified voltage [1–3, 5, 8–12].

SYSTEM DESIGN

A thermoelectric module (TEC-12706) is the first component of the proposed thermoelectric energy harvesting system. The other components are a candle-soot coating, a 784 cm² Fresnel lens, and a water block. The solar radiation was used for heating the upper surface of the TEG, and the water block provided flowing cold water for cooling the other side. The TEC1-12706 Thermoelectric module with dimensions 40 mm × 40 mm × 3.9 mm is used, which is based on Al₂O₃ material. The other specifications of the selected module are listed in Table 1. Before irradiating sunlight, the thermoelectric module was exposed to the direct flame of a candle to coat the layer of carbon soot on the upper surface.

EXPERIMENTAL SETUP

A mechanical structure assembly was placed to grasp the lens at the desired position to maximize the focused sun rays (Figures 1 and 2). Along with continuous heating from the top, the TEG was placed on an aluminum water block to maintain the temperature difference by cooling the bottom surface [4, 6, 13–15].

Table 1. Specifications of TEC1-12706.

Parameter	Value
Dimensions (mm)	40 × 40 × 4.2
Weight (grams)	17
Resistance (Ω)	0.85
No. of thermocouples	127
Max. current (Amps)	6.4
Max. voltage (Volts)	14.4
Max. power (Watts)	40
Max. temperature difference, ΔT (°C)	68
Hot-side temperature (°C)	80

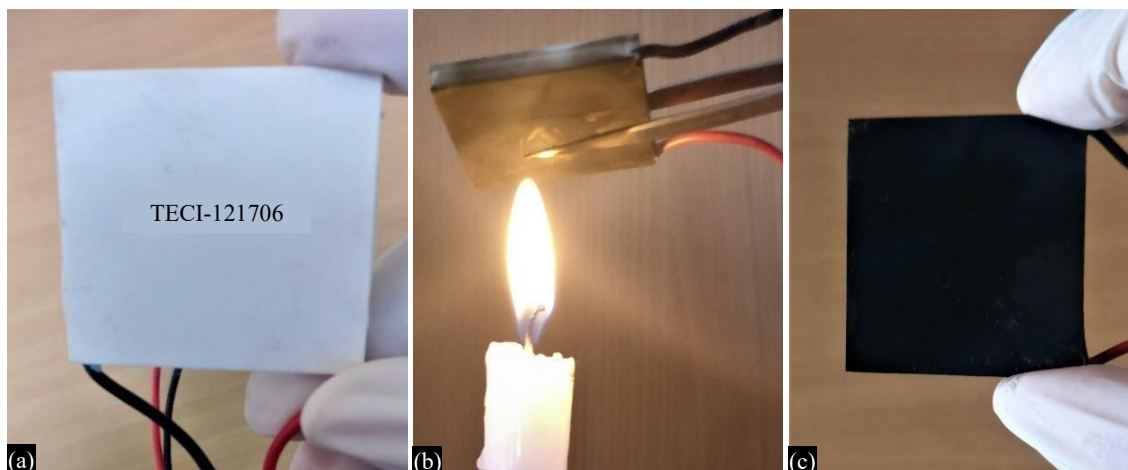


Figure 1. Candle-soot coating process. (a) Uncoated TEG module, (b) soot coating process, and (c) carbon soot-coated TEG module.

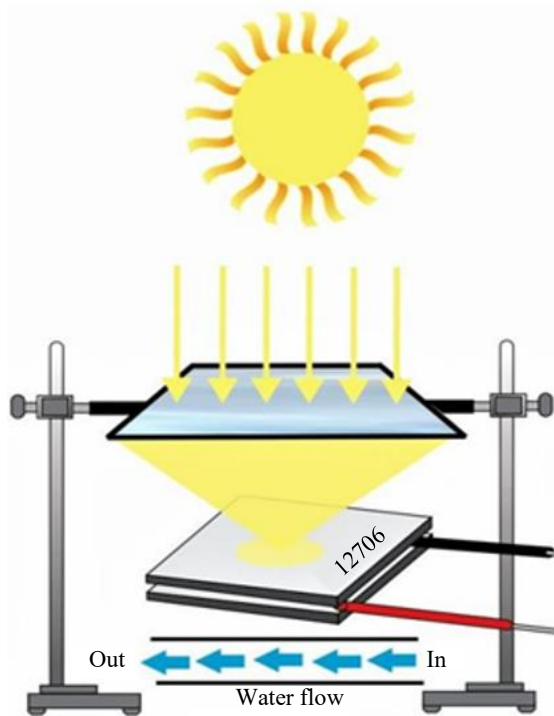


Figure 2. Schematic of thermoelectric generator system.

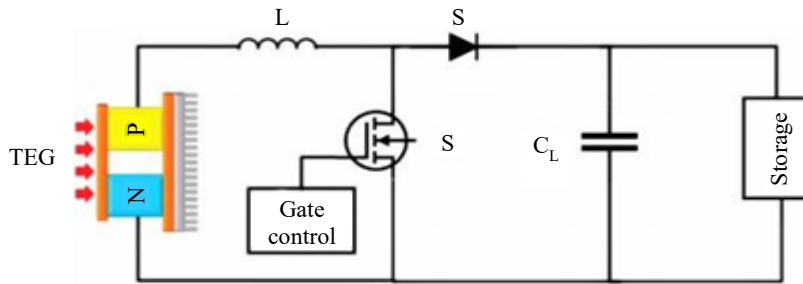


Figure 3. DC-DC boost converter.

Figure 3 shows an electrical DC-DC boost converter circuit for raising the voltage obtained from the TEG to further charge a 2.4 V battery. The basic design consists of the following components.

Schottky diode, D (BAT86), a 30 mH inductor (L),

A 4.7 μF capacitor (C_L) and a 2N7000 metal-oxide-semiconductor field-effect transistor (MOSFET) switch (S).

In ideal conditions, the above lossless components will generate an output voltage V_{out} categorized by the duty cycle of the MOSFET switching speed. The output voltage V_{out} is given by Equation (1) below:

$$V_{\text{out}} = \frac{V_i}{1-d} \quad (1)$$

The duty cycle, d , can be varied using a pulse width modulation (PWM) method in which the fixed width of a pulse, T_{on} , is changed instantaneously.

High-speed switching MOSFETs control the swift ON-OFF switching time and thereby regulate the output voltage level. The electrical parameters of the thermoelectric generator were measured to analyze the system performance (Table 2).

Table 2. Accuracies of measuring instruments.

Instrument	Parameter	Accuracy	Range
Fluke logging meter	DC	0.05%	500 μ A–10 A
	DC voltage	0.025%	50 mA–1000 V
Thermocouple	Temperature in $^{\circ}$ C	$\pm$ 2.2 $^{\circ}$ C	-40 to 260 $^{\circ}$ C

A 50 Ω resistor was connected at the load side to record the open-circuit voltage (V_{oc}), output load current (I), cold-side temperature (T_c), and hot-side temperature (T_h) using the following instruments [16–30]:

1. Electronic logging meter, Fluke 287, for recording the output current and voltage.
2. A K-type thermocouple for recording hot and cold-side temperatures.
3. A common submersible pump for garden usage that circulates water in a water block.

RESULTS AND DISCUSSION

The X-ray Diffraction (XRD) pattern shown in Figure 4 was obtained using a Cu-K-based Rigaku diffractometer with a 9-kW rotating anode to uniquely characterize the Chitosan-coated (CS) coated surface of the module.

The presence of amorphous carbon material is confirmed by the visible high-intensity peak at the 24.6 $^{\circ}$ 2θ position. Another low-intensity broad peak seen at the 43.16 $^{\circ}$ 2θ position indicates the presence of low-quality carbon particles [31–40]. These results correspond to the reported findings during a characteristic study of carbon nanoparticles present in candle wax, kerosene, and diesel [16, 17]. The peaks appearing at 24.6 $^{\circ}$ and 43.16 $^{\circ}$ correspond to a hexagonal (graphite) structure for (002) and (111) planes of carbon particles, respectively. Figure 5(a) shows the Raman spectrum of incident light, and the soot particles' absorption of visible, near-infrared, and ultraviolet light is seen in Figure 5(b).

The Raman spectrum provides details on how light is scattered by the vibrations of the irradiated molecules, highlighting information about the crystal lattice. A typical 535 nm green laser from HORIBA, Model: Lab Ram Hr Evolution, was used to irradiate the coated module at a grating rate of 1800 lines per millimeter. At room temperature, the intensity of the dispersed wavelength was measured in relation to the wavenumber (1/wavelength) in the range of 100–2000 cm^{-1} . The presence of projecting peaks is consistent with the intensity fluctuations predicted by several carbon-based vibration mode structures. The peak at 1350 cm^{-1} is caused by amorphous carbon, structural flaws, and sp^3 -hybridized carbon. The existence of sp^2 -oriented C-C stretched bonds in soot causes another peak to arise at 1590 cm^{-1} . Certain disordered quantities of carbon material present in soot are linked to the weaker Raman band at 1480 cm^{-1} . For the spectrum range of 2400–1200 nm, which falls in the NIR region, a gradual increase in absorbance value was observed. The absorption value in the NIR-UV region between 1200 and 370 nm increased noticeably when compared to the region below 370 nm, where it decreased rapidly.

According to scanning electron micrographs, the diameter of carbon particles ranges from 30 to 40 nm (not shown here) [41–55]. Figure 6 shows the open-circuit voltage generated by TEG for uncoated and coated samples from L0 to L4.

Because of the consistent rise in temperature differential between the two sides of the four-time-coated module, the L4 sample unquestionably produced the best results. Up to the fourth coating, the temperature differential increased before declining. The temporal temperature differential is determined by the amount of heating that reaches a thermoelectric material. As the candle-soot thickness rose, the thermoelectric sample surface could not be able to absorb heat, which would reduce the output voltage. While the uncoated module L0 could only provide 0.22 V, the voltage in the L4 sample increased dramatically to 1.46 V. Compared to the uncoated sample, the open-circuit voltage across the four-time-coated sample increased more than six times more rapidly. The amount of heat applied to all the coated and uncoated samples is a major factor in this increase.

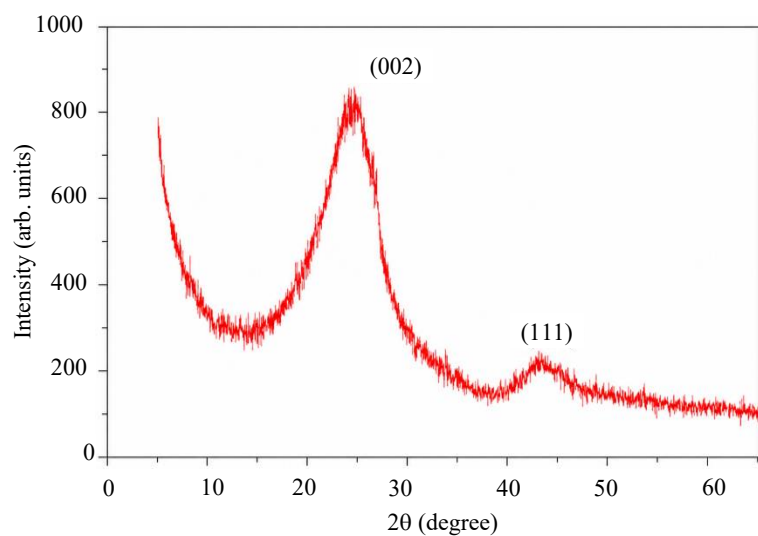
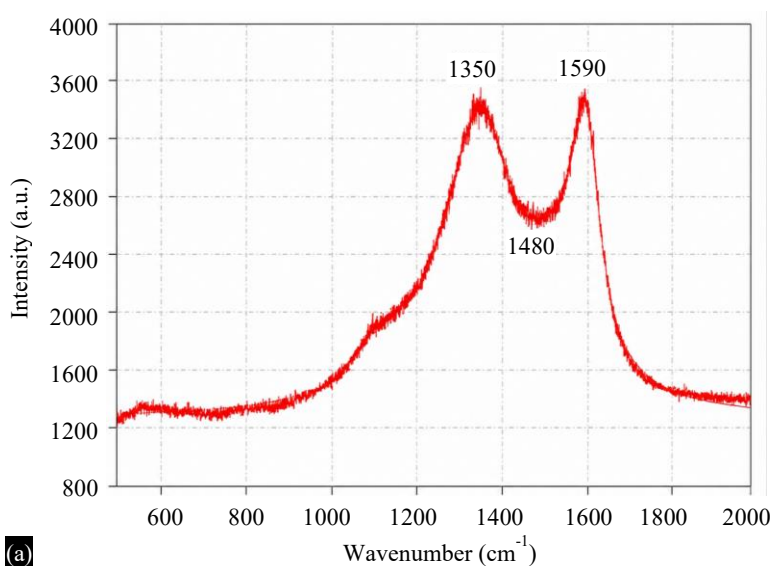
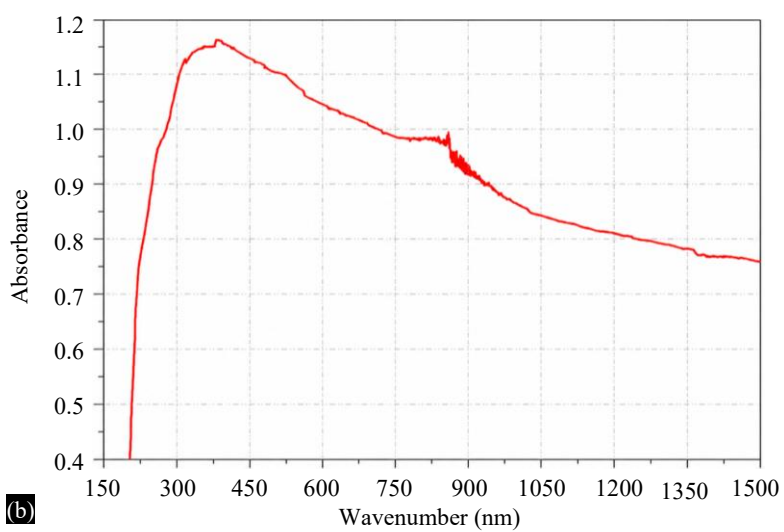


Figure 4. XRD pattern of carbon soot-coated thermoelectric module.



(a)



(b)

Figure 5. Spectrum graphs. (a) Raman Spectrum (b) NIR-UV-visible spectrum of carbon soot-coated thermoelectric module.

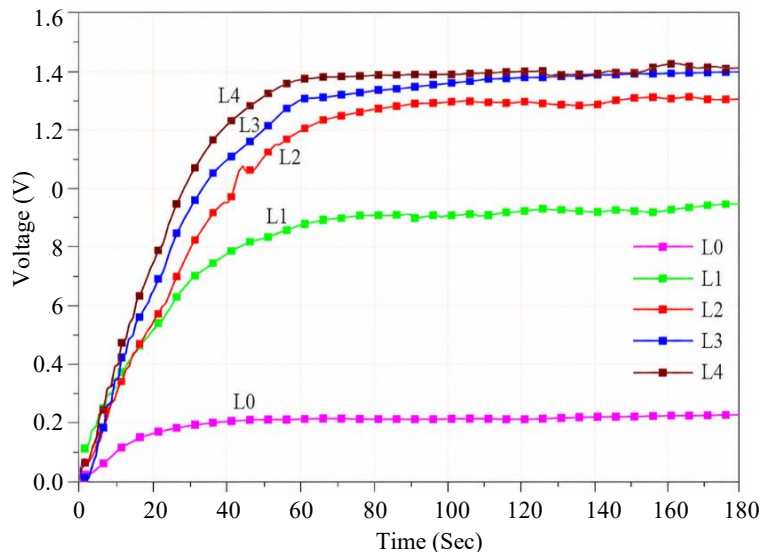


Figure 6. Open-circuit TEG output voltage.

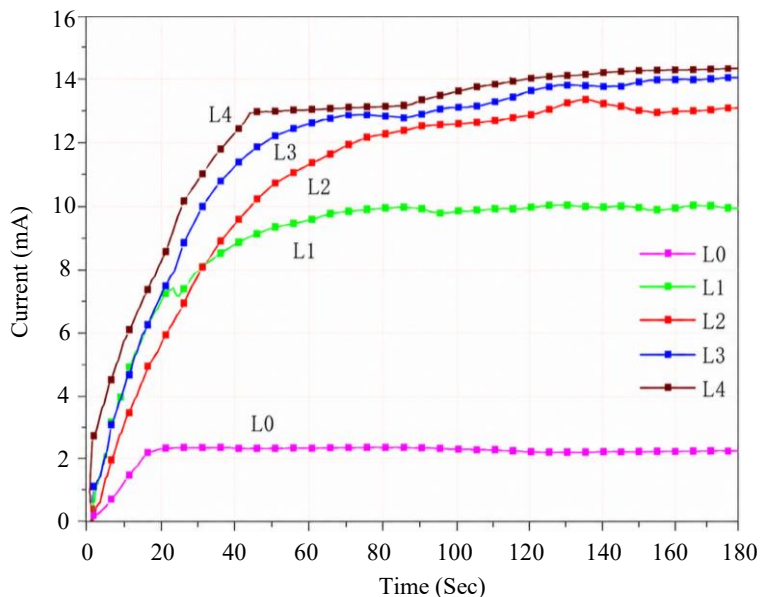


Figure 7. Load current from TEG.

The findings also show that the coated thermoelectric module had a much higher load current than the untreated sample [56–60]. Figure 7 shows the current across the 50Ω load resistor.

While the uncoated module (L0) could only produce 2.2 mA across the load by applying constant heating and cooling on both sides of the module, a maximum short-circuit current of 14.2 mA was observed utilizing the L4 sample [61–70]. Due to the strong heat absorption across the four times the candle-soot-coated sample, an astonishing rise of more than six times the uncoated module value was seen. The graphs for the output power obtained by the uncoated and coated samples over a load resistance of 50Ω following sequential 180 s of heating and cooling are displayed in Figure 8. The temperature gradient graph for the uncoated and coated samples over the two sides of the thermoelectric module is shown in Figure 9. The L4 sample produced a maximum power of 10.2 mW with a maximum current of 14.2 mA, but the uncoated TEG module had a lower output power of 0.24 mW. When compared to uncoated modules, this indicates a significant increase of over 42 times by four times coated modules. The candle-soot-coated TEG modules clearly performed better than the normal uncoated modules by producing noticeably greater electrical outputs.

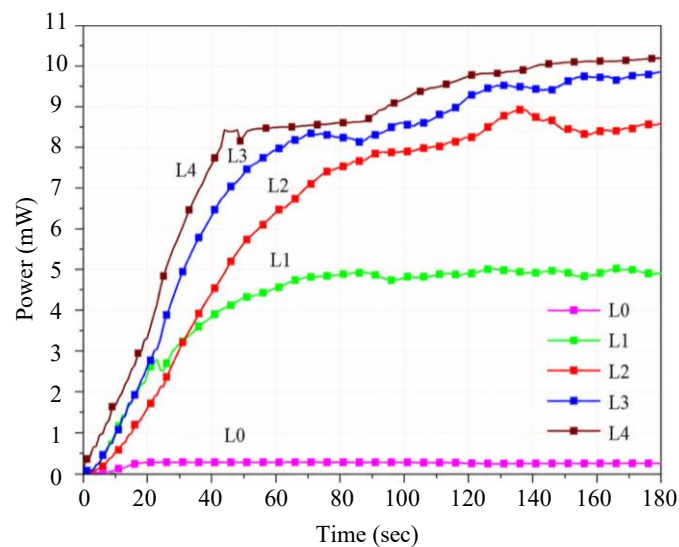


Figure 8. Output power from TEG.

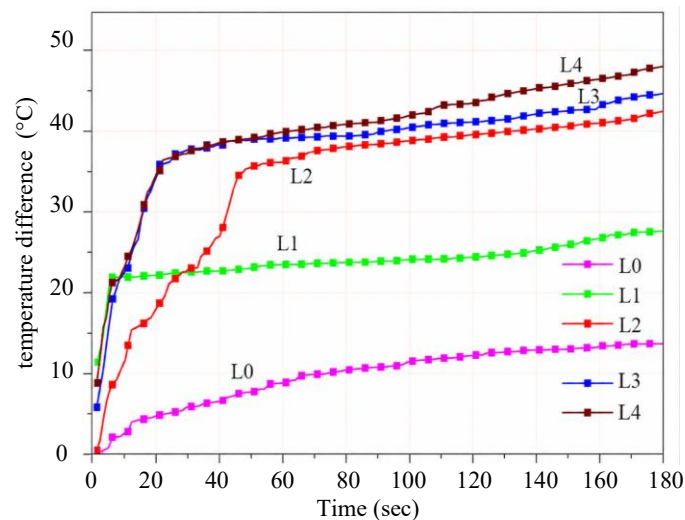


Figure 9. Temperature gradient of TEG.

Figure 10 displays a comparison of the TEG output voltage, current, and associated temperature differential measurements for uncoated and coated samples over 60 s. Four layers of carbon soot on the thermoelectric cell provide the greatest open-circuit voltage, as shown in Figure 10(a), whereas other lower-coated samples produce a lower voltage value. All the coated samples show a noticeable rise in voltage when compared to the untreated samples. As the number of soot layers increased, the corresponding maximum output voltage also increased. As evident from the plots, even the L1 sample (single coat module) showed a remarkable increase in the output voltage being generated from a conventional TEG cell.

With further consecutive layers of carbon soot, the voltage increased with each coated layer up to the fourth layer. The results from further soot layers were not recorded as the voltage began to decrease after four layers of carbon coating. Similarly, the short-circuit current values are shown in Figure 10(b) for L4 and the other samples. When compared to other cases under consideration, the current also rises with each consecutive layer of carbon soot coating. A remarkable increase in current value was recorded after the first soot layer as compared to the output current from the uncoated cell. This sequential increase in output voltage and current values was credited to a gradual corresponding increase in the temperature difference. The plots in Figure 10(c) show the temperature gradient was

created on two sides of the uncoated and coated samples to increase the electrical output. The corresponding recorded values for open-circuit voltage, short-circuit load current, and the temperature difference generated across the TEG are listed in Table 3. The maximum voltage reached 1.37 V when recorded for the first 60 s of system operation.

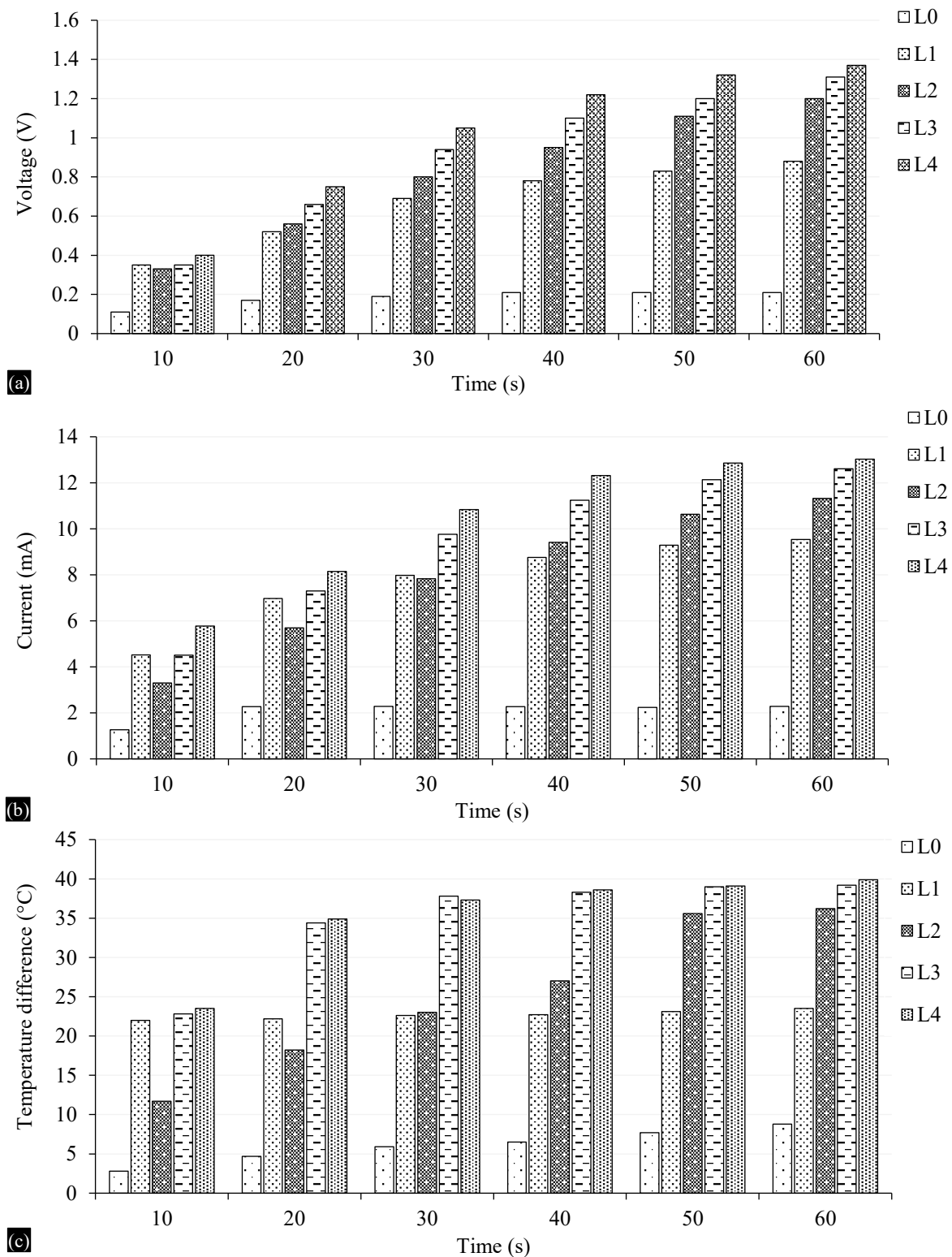
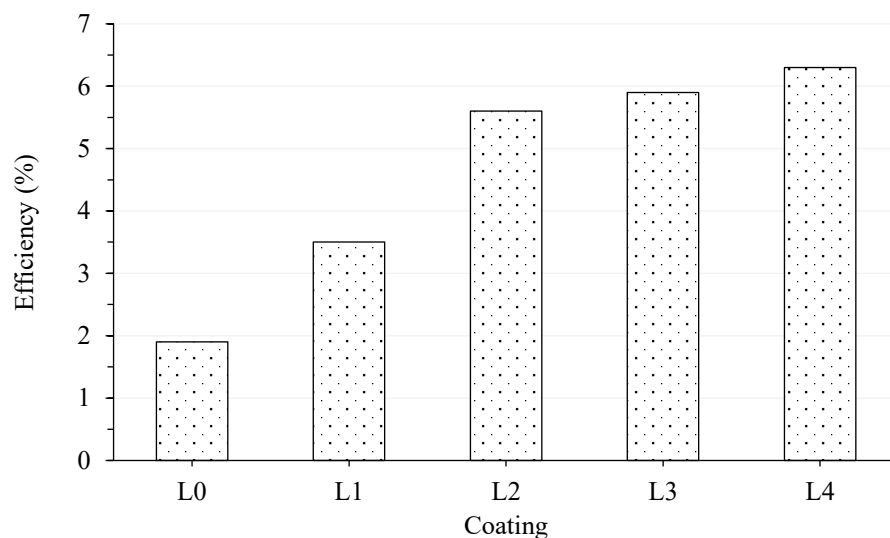


Figure 10 TEG electrical outputs (a) open-circuit voltage, (b) short-circuit current, and (c) temperature difference.

Table 3. Voltage and current obtained for corresponding temperature difference L0, no coating; L1, one coat; L2, two coats; L3, three coats; L4, four coats.

Time (s)	Voltage (V)					Current (mA)					Temperature difference (°C)				
	L0	L1	L2	L3	L4	L0	L1	L2	L3	L4	L0	L1	L2	L3	L4
10	0.11	0.35	0.33	0.35	0.40	1.27	4.52	3.30	4.51	5.77	2.8	22.0	11.7	22.8	23.5
20	0.17	0.52	0.56	0.66	0.75	2.27	6.97	5.69	7.30	8.14	4.7	22.2	18.2	34.4	34.9
30	0.19	0.69	0.80	0.94	1.05	2.28	7.98	7.83	9.76	10.84	5.9	22.6	23.0	37.8	37.3
40	0.21	0.78	0.95	1.10	1.22	2.27	8.76	9.41	11.24	12.32	6.5	22.7	27.0	38.3	38.6
50	0.21	0.83	1.11	1.20	1.32	2.24	9.29	10.63	12.13	12.86	7.7	23.1	35.6	39.0	39.1
60	0.21	0.88	1.20	1.31	1.37	2.28	9.53	11.32	12.61	13.03	8.8	23.5	36.2	39.2	39.9

**Figure 11.** Maximum energy conversion efficiency (L0, no coating; L1, one coat; L2, two coats; L3, three coats; L4, four coats).

To show the effectiveness of the system to successfully convert the thermal energy to electrical energy, the conversion efficiency of the system was calculated. Figure 11 shows the energy conversion efficiency plot of the system under consideration. The value of the Seebeck coefficient (α) required for efficiency calculations was calculated for uncoated cells and all the coated cells individually. The efficiency readings for all the candle-soot coated samples (L1–L4) showed a significant increase as compared to the efficiency of uncoated samples. The efficiency readings for all the candle-soot coated samples (L1–L4) showed a significant increase as compared to the efficiency of the uncoated sample. The average temperature difference created across the uncoated cell was 9.8°C with a maximum temperature difference of 13.8°C. The average temperature gradient of 40.3°C was achieved across the L4 coated sample with a maximum value reaching 48°C.

As evident from Figure 11, the efficiency of the system was maximum when integrated with four soot layers coated thermoelectric module. A maximum conversion efficiency of 6.3% was achieved by the system for converting the heat energy from the sun to electrical energy. This performance was recorded by the corresponding temperature difference of 48°C at the end of 180 s by the L4 sample.

It was observed that the uncoated cell showed 1.9% conversion efficiency for a maximum temperature gradient of 13.8°C. Looking at the results for other coated modules, L1, L2, and L3 gave maximum efficiencies of 3.5%, 5.6%, and 5.9%, respectively. The results clearly showed that coating the cells with a carbon material-based candle-soot layer enhanced the overall system efficiency by 4.4%.

Table 4. Comparative analysis of thermoelectric generators.

Ref.	Thermoelectric module	No. of modules	Coating	Concentrator	Heating source	Open-circuit voltage (V)	Current (mA)	Power (mW)	Efficiency (%)
Lin et al. [61]	NA	1	Cu NPs@Zn foil, Ck@membrane, RGO@Ni foam	—	Xenon lamp	0.21	1.34	0.28	NA
Sudharshan et al. [71]	NA	3	Al alloy	Glass plate	Solar radiation	0.8	55.25	44.2	0.82
Ogbonnaya et al. [72]	1261G-7L31-04CQ	1	Nickel-tin coating on Cu plate	—	Halogen lamp	0.13	70.38	9.15	NA
Köysal et al. [73]	TEG1-12611-8.0	2	Graphene	Fresnel lens	Solar radiation	1.41	193.61	273	0.6

The additional layer of soot for enhanced heat absorption made the system almost four times more efficient than a conventional uncoated cell-based thermoelectric system. A DC–DC boost converter was used to increase the 1.46 V output voltage from L4 to charge a 2.4 V rechargeable VARTA battery to assess the system’s energy storage capacity. By periodically energizing a 30 mH inductor, the output was increased to a slightly higher value of 2.4 V to charge a 4.7 μ F capacitor.

CONCLUSION

This chapter presents an experimental investigation of using a thermoelectric module covered with candle soot to harvest thermoelectric energy. A temperature differential was produced between two of the module’s surfaces by focusing sunlight and moving water. The module was coated with different thicknesses of candle soot using a candle flame, and the crystal morphology was examined using Raman spectroscopy. When coated with the fourth consecutive CS layer, a maximum of 1.46 V of open-circuit voltage and 14.2 mA of peak current were obtained. This is a significant improvement over a conventional (uncoated) thermoelectric module, which has a maximum voltage of 0.22 V and a peak current of 2.2 mA. The 10.2 mW harvested power from the soot-coated TEG is reported to outperform the conventional uncoated module with only 0.24 mW of power. This technique also yields an electrical conversion efficiency of 6.3%. A rechargeable battery was also charged in 1.5 h to illustrate the energy storage application. Low- and ultra-low-power sensors and other electronic equipment can be powered by the stored energy. By cascading many TEG modules, the harnessed output power can be further boosted. However, the impedance matching of such a setup should be examined for maximum power transmission.

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