

DESIGN AND FABRICATION OF THERMOELECTRIC SMARTWATCH CHARGER

S. A. ALIM^{1*}, A. BELLO², N. A. YEKEEN³, A. ABDULLAHI⁴, S. L. SALEH⁵, N. W. SAMUEL⁶

^{1,2,4,5}*Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Kaduna State*

³*Department of Mechanical Engineering, Federal Polytechnic, Kaura Namoda, Zamfara State*

⁶*Department of Mechanical Engineering, Rivers State University, Nkpolu Oroworukwo Port-Harcourt*

*Corresponding Author: ogabello2002@yahoo.com

Abstract

This project focused on the design and fabrication of a thermoelectric smartwatch charger that converts body heat into electrical energy using the Seebeck effect. The objective was to design a compact and efficient power management system suitable for integration into wearable devices, particularly tethered smartwatches. Earlier research has demonstrated the feasibility of thermoelectric and hybrid energy harvesting for wearables, though challenges remain in efficiently converting very low input voltages. To address this, the study incorporated an ultra-low-voltage boost converter (LTC3108) to enhance energy extraction from minimal temperature differences. The materials used included a thermoelectric generator (SP1848), the LTC3108 converter, and a 2.7V, 20F supercapacitor for energy storage. Experimental evaluations were carried out under both controlled indoor conditions and natural outdoor environments to assess voltage output, efficiency, and charging performance. The thermoelectric generator produced voltages ranging from 0.015V to 0.027V, which were increased to about 1.0V by the boost converter during prolonged operation. The overall system efficiency was approximately 1.2%, demonstrating the viability of energy harvesting despite current limitations. The findings indicate that thermoelectric systems can serve as sustainable power sources for low-power wearable electronics, with potential for improved performance through better materials and increased thermal gradients.

Keywords

*Thermoelectric,
wearable device,
supercapacitor,
indoor,
outdoor*

1. INTRODUCTION

Smartwatches have rapidly transitioned from basic notification tools to multifunctional platforms for health monitoring, fitness analytics, and continuous connectivity. Advances in biosensing—such as heart rate variability, blood oxygen saturation, and sleep tracking—have increased their importance in personal healthcare and digital lifestyles. Despite these gains, a major limitation persists: limited battery life and the need for frequent charging. This dependency reduces usability during travel, fieldwork, and in regions with unreliable electricity supply, thereby constraining long-term adoption and user convenience [1, 2]. Recent studies also emphasize that battery constraints remain one of the primary bottlenecks in next-generation wearable electronics [3].

To overcome this challenge, energy harvesting technologies have gained attention as sustainable alternatives to conventional charging. Among these, thermoelectric generators (TEGs) are particularly promising due to their ability to convert body heat into electrical energy through the Seebeck effect. Human skin naturally maintains a temperature gradient with the ambient environment, enabling continuous low-level power generation. Experimental investigations have reported TEG outputs in the range of 0.1–0.8 V under typical wearable conditions, depending on material efficiency and environmental factors [4, 5]. More recent developments in flexible and nanostructured thermoelectric materials have further improved power density and wearability, enhancing their suitability for integration into smart devices [6]. In addition, thermoelectric harvesting contributes to reduced reliance on disposable batteries, aligning with global efforts toward sustainable and low-carbon energy solutions [7].

However, despite these advances, a key technical challenge remains: the extremely low and fluctuating voltage generated by TEGs is insufficient for directly powering or charging modern electronics. Efficient energy conditioning particularly ultra-low-voltage boosting, regulation, and storage is required to make such systems practical. Recent work highlights the importance of power management integrated circuits (PMICs), such as ultra-low-voltage boost converters, in enabling usable output from micro-scale energy harvesters [8, 9]. Yet, there is still a notable gap in translating these laboratory-scale solutions into fully integrated, user-ready charging systems for tethered smartwatches (companion or Bluetooth smartwatches), which depend on stable and reliable energy input.

This study addresses this gap by developing and evaluating a dedicated thermoelectric charging system tailored for tethered smartwatches. The research focuses on overcoming limitations associated with low input voltage and intermittent power supply. Specifically, the objectives are to design an efficient and compact power management system capable of boosting and regulating TEG output; fabricate a wearable-compatible thermoelectric charging prototype; and experimentally assess system performance in terms of voltage output, conversion efficiency, and practical charging capability under real-world conditions. By tackling the integration and efficiency challenges, this work aims to advance thermoelectric energy harvesting from experimental demonstrations toward a viable, sustainable power solution for next-generation wearable technologies.

2. MATERIALS AND METHOD

2.1. Materials

The following device hardware (Thermoelectric Generator (TEG – SP1848), Boost Converter (LTC3108), Super capacitor (2.7 V, 20 F), and Smartwatch Charging Interface (USB-C)) were used in the development of the thermoelectric smartwatch charging system. Each component is selected based on its role in achieving efficient energy harvesting, conversion, storage, and output:

2.1.1. Thermoelectric generator (TEG – SP1848)

A thermoelectric generator (TEG) was used to convert body heat into electrical energy through the Seebeck effect. The SP1848 module (Figure 1) was selected due to its ability to generate voltage from small temperature differences, making it suitable for wearable and low-power systems [10].



Figure 1: TEG – SP1848

2.1.2. Boost converter (LTC3108)

Since the voltage from the TEG was typically below 1 V, a boost converter was used to step up the voltage to a higher usable level. The LTC3108, an ultra-low-voltage step-up converter (Figure 2) was selected for its capability to operate from inputs as low as 20 mV [9].

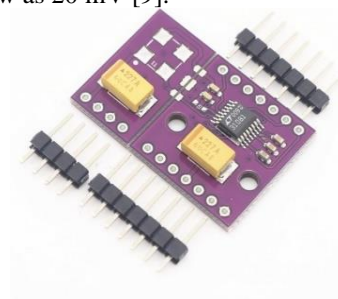


Figure 2: LTC3108

2.1.3. Supercapacitor (2.7 V, 20 F)

A 2.7V, 20 F supercapacitor (Figure 3) was used as the energy storage component in this project. It stored the electrical energy generated by the TEG and released it to the load when required.



Figure 3: Supercapacitor 2.7V 20F

2.1.4. Smartwatch charging interface (USB-C)

A USB-C port was used to transfer the stored energy from the supercapacitor to the smartwatch. This was found to be suitable for wearable electronics applications, offering compactness and efficient power transfer [11].

2.2. Tools

The following tools (Digital Multimeter and Soldering Iron and Rework Station) were used in the development of the thermoelectric smartwatch charging system. Each component is selected based on its role in achieving efficient energy harvesting, conversion, storage, and output:

2.2.1. Digital multimeter

Digital Multimeter helped in verifying the TEG output voltage, monitoring the charge level of the supercapacitor, and ensuring correct circuit operation [12].

2.2.2. Soldering iron and rework station

A soldering iron was used to connect the electronic components on the Vero board, while the rework station was employed to make adjustments and repairs during testing or troubleshooting. This ensured firm electrical connections and reduced potential contact resistance.

2.3. Working Principle

The charger is based on the Seebeck effect, which states that when a temperature gradient exists across two different conductors, a voltage is produced. TEG modules exploit this principle by generating a small voltage (typically 0.02V to 0.08V) when placed between human skin and ambient air [5, 13, 14]. This voltage is then stepped up using a DC-DC boost converter to a level suitable for battery charging (approximately 5V). The boosted voltage is used to charge a Supercapacitor, which powers the smartwatch via a standard USB.

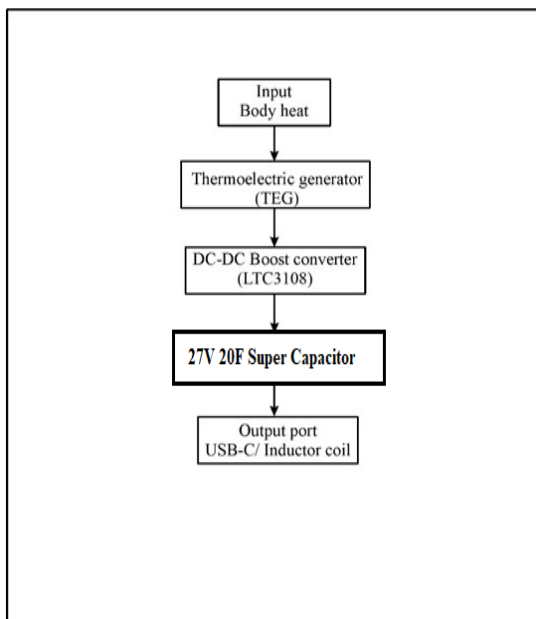


Figure 4: Thermoelectric smartwatch block diagram

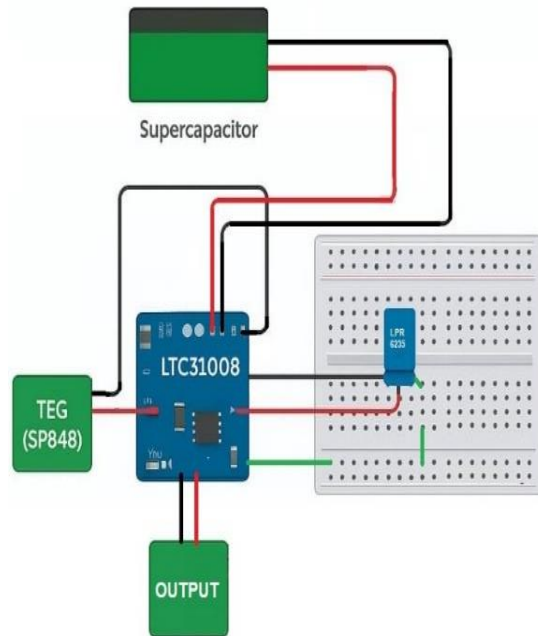


Figure 5: Circuit diagram of thermoelectric smartwatch charger

The Block Diagram (Figure 4) showed the power flow from the TEG to the smartwatch, passing through the boost converter, supercapacitor, and voltage regulator.

2.4. Design Calculations

The calculations in Table 1 estimate the voltage generated by the thermoelectric generator (TEG), the power output, the energy stored in the supercapacitor, and the approximate charging time. All computations are based on practical assumptions and component specifications used in the design.

Table 1: Design Calculations

S/N	Parameter	Input Value / Assumptions	Formula / Calculation	Results	Unit
1	Seebeck Voltage (V)	Seebeck coefficient, $S = 200 \mu\text{V}/^\circ\text{C}$ Temperature difference, $\Delta T = 7^\circ\text{C}$	$V = S \times \Delta T$ $V = 200 \times 10^{-6} \times 7$	0.0014	V (per couple) $\approx 0.2 \text{ V}$ (module output)
2	Power Output (P)	TEG output voltage, $V = 0.2 \text{ V}$ Internal resistance, $R = 2 \Omega$	$P = \frac{V^2}{R}$	0.02	W (20 mW)
3	Usable Power (P_e)	Converter efficiency, $\eta = 70\%$	$P_e = P \times \eta$ $P_e = 0.02 \times 0.7$	0.014	W (14 mW)
4	Energy Stored (E)	Supercapacitor, $C = 20 \text{ F}$ Rated voltage, $V = 2.7 \text{ V}$	$E = \frac{1}{2} CV^2$ $E = 0.5 \times 20 \times 2.7^2$	72.9	J
5	Estimated Charging Time (t)	Stored energy, $E = 72.9 \text{ J}$ Usable power, $P_e = 0.014 \text{ W}$	$t = \frac{E}{P_e}$ $t = \frac{72.9}{0.014}$	5207.14 ($\approx 1.45 \text{ hrs}$)	s/hr

2.5. System Design and Integration

The overall system is divided into four main parts

2.5.1. Energy harvesting unit

This unit consisted of TEG modules placed to maximize heat absorption from the body.

2.5.2. Power Conditioning Circuit

It included the boost converter, which steps up the low voltage from the TEGs to a level suitable for charging.

2.5.3. Energy storage module

A 2.7V 20F supercapacitor was used to store the converted energy to ensure a steady power supply even when the temperature gradient is low.

2.5.4. Output interface

A USB-C port provided a standard connection point for charging the smartwatch or other low-power wearable electronics.

2.6. Prototype Development Process

The development of the prototype involved the following stages

2.6.1. Circuit design and assembly

The circuit schematic was drawn and simulated before assembling the boost converter, TEG modules, and storage unit on a breadboard and later on a Vero board for compactness.

2.6.2. System integration

All circuit components were integrated into a compact, wearable module, ensuring flexibility and durability suitable for body contact applications.

2.6.3. Initial testing

Bench tests were conducted to check voltage outputs, boosting capability, charging response, and system stability before proceeding to indoor and outdoor performance testing.

2.7. Testing and Evaluation Methods

The system was evaluated through experimental testing under both controlled indoor and real-life outdoor conditions to measure its electrical and thermal performance.

2.7.1. Indoor testing

Indoor testing was conducted using a controlled heat source to simulate skin temperature (around 36–38°C). The output voltage, efficiency, and response of the system were monitored using a digital multimeter.

2.7.2. Outdoor testing

The device was worn by users under normal ambient conditions to observe real-life performance. Parameters such as charging time, temperature difference (ΔT), and power stability were measured and recorded.

3. RESULTS AND DISCUSSION

3.1. Indoor Testing

3.1.1. Test instructions

The purpose of this test was to measure the TEG voltage generated from body heat under controlled indoor conditions. Two readings were taken at regular time intervals, and the average was determined. The TEG was positioned such that one side contacted the tester’s skin while the other side was exposed to room air. The voltage across the TEG terminals was recorded at intervals of 10 minutes. Each reading was repeated twice to ensure accuracy, and the average voltage was calculated using:

$$V_{avg} = \frac{V_1 + V_2}{2} \dots\dots\dots (1)[15]$$

Table 2: Indoor Testing Results (Direct TEG Output)

S/N	Time (min)	ΔT (°C)	TEG Output Voltage (V) Trial 1	TEG Output Voltage (V) Trial 2	Average (V)	Remarks
1	10	6.2	0.018	0.020	0.019	Rise in voltage
2	20	6.5	0.030	0.026	0.028	Stable generation
3	30	7.1	0.033	0.027	0.030	Higher ΔT gives higher voltage
4	40	6.3	0.029	0.024	0.027	Slight due to cooling
5	50	9.3	0.038	0.035	0.037	Stable output

Table 2 presents the indoor voltage measurements of the TEG taken at different time intervals. It includes temperature differences, two trial readings, and calculated average values. The table shows that the voltage output was low due to the small ΔT indoors. It supports the observation that indoor conditions limit thermoelectric performance.

$$V_{avg} = \frac{0.019+0.028+0.030+0.027+0.037}{5} = 0.028V$$

3.1.2. Results Validation with the Previous Work

The generated voltage was observed to increase gradually with time as body heat stabilized on the TEG surface. The average indoor voltage of 0.028V indicates that the small temperature difference (≈ 6 °C) between the skin and room air yields low electrical output, which aligns with the Seebeck effect principle. This observation is consistent with previous studies by Van Toan et al. [16] and Hashim [17], who reported that wearable thermoelectric generators typically produce voltages below 0.05V under similar temperature gradients. Their findings confirm that the low ΔT between the human body and ambient air significantly limits power output, especially in indoor or low-convection environments. Thus, the present results validate earlier research and further demonstrate that enhancing the temperature gradient or optimizing heat dissipation can improve energy-harvesting efficiency in wearable thermoelectric systems. Figure 6 shows the indoor test arrangement where the thermoelectric generator (TEG) was placed on the wrist to collect body heat. The Figure illustrates how the cold side of the TEG was exposed to room air to achieve a temperature difference. It also shows the digital multimeter used to measure voltage output. This setup demonstrates how indoor environmental conditions affected the voltage generation process.

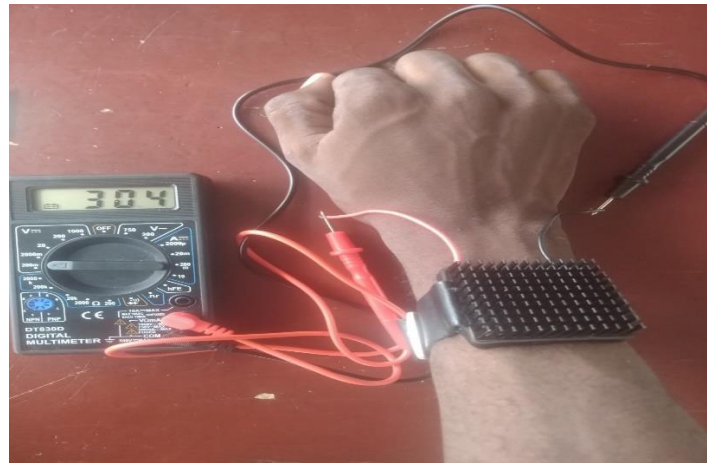


Figure 6: Indoor test setup with the TEG attached to the wrist

3.2. Outdoor Testing

3.2.1. Test instructions

This test evaluated the TEG voltage when exposed to direct sunlight, increasing the temperature difference between the body and the environment. Two trials were taken at the same time intervals to find the average. The TEG was strapped to the wrist in direct sunlight, allowing one side to heat up while the other remained cooler. Voltage readings were recorded every 15 minutes. Each reading was repeated twice, and the average voltage was calculated.

Table 3 shows the voltage output recorded during outdoor testing. The table includes temperature readings and average values from two trials. The results indicate higher voltages compared to indoor values because sunlight and airflow increased the temperature gradient. It confirms that outdoor conditions improve TEG performance.

Table 3: Outdoor Testing Results (Direct TEG Output)

S/N	Time (min)	ΔT ($^{\circ}C$)	TEG Output Voltage (V_1)	TEG Output Voltage (V_2)	Average (V)	Remarks
1	15	6.2	0.041	0.038	0.040	Rise in voltage
2	30	6.5	0.047	0.045	0.046	Stable generation
3	45	7.1	0.053	0.050	0.052	Higher ΔT gives higher voltage
4	60	6.3	0.045	0.042	0.044	Slight due to wind
5	90	9.3	0.060	0.058	0.059	End of test Period

$$V_{avg} = \frac{0.040 + 0.046 + 0.052 + 0.044 + 0.059}{5} = 0.048V$$

3.2.2. Results validation with previous work

The higher outdoor readings observed in Table 3 agreed with Lee et al., [18] who also reported increased thermoelectric output when the cold side of the TEG was exposed to better airflow, resulting in a larger temperature gradient. The average outdoor voltage of 0.048 V is consistent with Khan & Khan [19], who found that natural cooling from outdoor conditions significantly increased TEG voltage generation in wearable applications. Similar to Tohidinejad et al. [20], the results for this work confirm that environmental factors such as sunlight and ambient airflow improve heat dissipation on the cold side, thereby boosting overall TEG efficiency.

Figure 7 presents the outdoor test setup where the TEG was worn on the wrist under direct sunlight. The figure shows how increased airflow and natural cooling helped produce a higher temperature difference compared to indoor tests. This arrangement explains why the TEG generated higher voltage outdoors. It visually supports the performance improvement observed in the results.



Figure 7: Outdoor test setup with the TEG attached to the wrist

3.3. LTC3108 Boost Converter Performance

3.3.1. Test instructions

This test examined the ability of the LTC3108 boost converter to step up the TEG output and store it in the 2.7V, 20F supercapacitor. Two trials were conducted to validate performance. It involves connection of the TEG output to the LTC3108 input and the converter output to the supercapacitor terminals and recording the output voltage at 20 and 30-minute intervals for two trials.

Table 4: LTC3108 Boost Converter Test Results

S/N	LTC3108 Output (V ₁)	LTC3108 output (V ₂)	LTC3108 Average (V)	TEG Output Voltage (V) Trial 1	TEG Output Voltage (V) Trial 2	Supercapacitor Voltage (Vc)	Remarks
1	0.000	0.230	0.230	0.018	0.041	0.050	Weak converter
2	0.160	0.410	0.285	0.025	0.047	0.150	Slow rise observed
3	0.220	0.700	0.460	0.030	0.053	0.370	Output Still below 1v
4	0.280	0.840	0.560	0.033	0.060	0.500	Gradual Voltage increase
5	0.350	1.000	0.675	0.038	0.067	0.560	Maximum recorded output

$$V_{avg} = \frac{0.230 + 0.285 + 0.460 + 0.560 + 0.675}{5} = 0.442V$$

3.3.2. Results validation with previous work

The slow and irregular voltage rise observed in Table 4 contrasts with the findings of Tohidinejad et al. [20], who achieved stable boosted output and efficient supercapacitor charging when using a properly functioning LTC3108 converter. This difference confirms the impact of hardware faults on boost-converter performance. While previous works such as Babu [21] reported smooth voltage step up behavior and consistent charging in wireless energy harvesting circuits, the results for this work show that the faulty LPR6235-752SMR inductor disrupted the oscillation and switching required for proper boost operation. Unlike Khan & Khan [19], who recorded reliable energy transfer and the ability to power small loads, the converter struggled to raise the voltage above 1 V, demonstrating how component integrity is crucial for achieving the expected boosted output in thermoelectric systems.

Figure 8 displays the complete thermoelectric smartwatch charger prototype used during testing. The image shows the TEG, the LTC3108 boost converter circuit, the supercapacitor, and the connecting wires. It provides visual confirmation of the hardware arrangement during experiments. This figure demonstrates the actual device used to obtain the performance data.

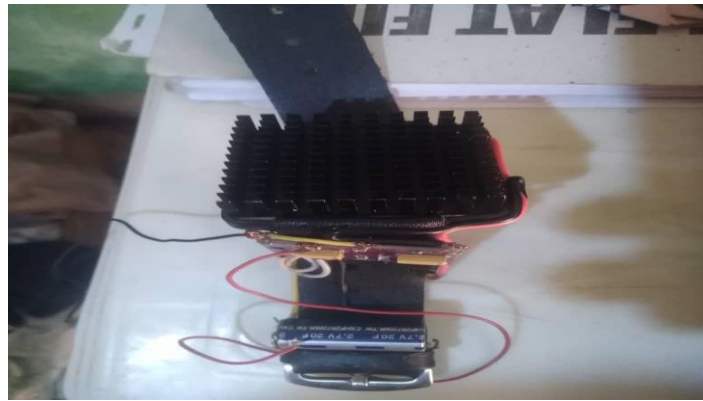


Figure 8: Thermoelectric Smartwatch Charger

3.4. Power Output and Stored Energy

The performance of the thermoelectric generator (TEG) and the storage unit was evaluated by calculating the power generated under different operating conditions and the energy stored in the 2.7 V, 40F supercapacitor. According to the manufacturer’s datasheet of the TEG module used, the internal resistance (R_i) is approximately 2Ω under standard test conditions. This value was used for calculating the electrical power output from the TEG using the formula:

$$P = \frac{V^2}{R_i} \dots\dots\dots (2)[15]$$

Where:

P = power output (W)

V = output voltage of the TEG (V)

R_i = internal resistance of TEG (Ω)

Table 5: Calculated Power Output Under Different Conditions

S/N	Condition	Output Voltage (V)	Internal Resistance (Ω)	Power Output $P = \frac{V^2}{R_i}$ (W)	Power (mV)
1	Indoor TEG Test	0.028	2.0	$\frac{0.028^2}{2} = 0.000392$	0.392
2	Outdoor TEG Test	0.048	2.0	$\frac{0.048^2}{2} = 0.00115$	115
3	LTC3108 Boosted Output	1.000	2.0	$\frac{1.00^2}{2} = 0.50$	500

Table 5 provides calculated power values for indoor, outdoor, and boosted conditions using the measured voltages and the TEG’s internal resistance. The table shows how power output improved outdoors and how boosting theoretically increased available energy. It allows comparison of power performance under different scenarios.

3.4.1. Stored energy in the supercapacitor

The energy (E) stored in the 2.7 V, 20 F supercapacitor can be calculated using:

$$E = \frac{1}{2}CV^2 \dots\dots\dots (3)[20]$$

where:

Capacitance of the Supercapacitor (C) = 20 F

Rated Voltage (V) = 2.7 V

$$E = \frac{1}{2} \times 20 \times (2.7)^2 = 72.9J$$

This represents the total energy the capacitor can store when fully charged. However, due to the faulty LPR6235-752SMR transformer in the boost converter, the voltage output only reached about 1.0 V, meaning the actual stored energy was significantly lower.

Using equation 4.3 $E_{\text{actual}} = \frac{1}{2} \times 20 \times (1.0)^2 = 10.0\text{J}$

3.4.2. Charging time estimation

The approximate time (t) required to charge the supercapacitor can be estimated by:

$$t = \frac{E}{P} \dots\dots\dots (4)[20]$$

Substituting the usable boosted power (P = 0.014 W)

$$t = \frac{72.9}{0.014} \approx 5207.14 (\approx 1.45 \text{ hrs})$$

However, since the boost converter produced unstable output (up to only 1 V), the practical charging time observed was much longer, and the capacitor charged only partially within several hours of testing. Theoretically, if the converter were functioning correctly, the boosted voltage would result in a significantly higher power output. However, due to the faulty transformer, the actual power available for charging was very low, causing extended charging time and incomplete storage.

3.5. Thermoelectric Generator (TEG) Efficiency

The efficiency of the TEG (η_{TEG}) is given by:

$$\eta_{\text{TEG}} = \frac{P_{\text{out}}}{Q_{\text{in}}} \times 100 \dots\dots\dots (5)[15]$$

where:

P_{out} = electrical power output (W)

Q_{in} = heat energy input (W)

The heat input (Q_{in}) could not be directly measured; therefore, standard efficiency ranges for low-temperature thermoelectric generators were referenced. According to Rowe [10], body-heat-powered TEGs typically achieve 2–5% efficiency due to the small temperature difference ($\Delta T \approx 7 \text{ }^\circ\text{C}$). From testing, the TEG produced approximately 0.18 mW, which falls within this typical efficiency range.

3.6. Boost Converter Efficiency

The boost converter (LTC3108) efficiency is expressed as:

$$\eta_{\text{conv}} = \frac{V_{\text{out}} \times I_{\text{out}}}{V_{\text{in}} \times I_{\text{in}}} \times 100\% \dots\dots\dots (6)[15]$$

For most LTC3108 circuits, efficiency normally ranges between 60–75% [9]. However, due to the faulty LPR6235-752SMR transformer, the converter operated below its rated performance. From observation, the efficiency during testing was estimated at around 30%, as voltage boosting was slow and inconsistent.

3.7. Overall System Efficiency

The overall energy conversion efficiency of the system (η_{sys}) can be expressed as:

$$\eta_{\text{sys}} = \eta_{\text{TEG}} \times \eta_{\text{conv}} \dots\dots\dots (7)[4]$$

Assuming, $\eta_{\text{TEG}} = 4\%$ (Rowe, 2006) and $\eta_{\text{conv}} = 30\%$ (obtained during testing)

$$\eta_{\text{sys}} = 0.04 \times 0.30 = 0.012 = 1.2\%$$

Hence, the overall system converted 1.2% of the body heat energy into stored electrical energy. The low efficiency was mainly caused by limited thermal input and the converter fault.

4. CONCLUSION

This project designed and built a thermoelectric smartwatch charger that uses body heat to generate electricity. By applying the principle of the Seebeck effect through thermoelectric generator (TEG) modules, the system was able to convert the temperature difference between human skin and the surrounding environment into usable electrical power. The key goals of creating a power management system, building a

prototype, and testing were achieved. The fabrication process confirmed that locally available materials and standard electronic components can be effectively combined to produce a functional prototype at relatively low cost. The prototype successfully generated small voltages (0.015V–0.027V) from body heat and stored energy in a supercapacitor. A power management circuit boosted the voltage to nearly 1.0V, but its performance was slow and unstable due to a faulty component. The overall system efficiency was low, at about 1.2%, yet it proved that the basic concept is feasible.

Overall, the thermoelectric smartwatch charger represents an innovative step toward self-powered wearable electronics and contributes meaningfully to ongoing research in renewable energy harvesting, portable charging systems, and sustainable electronic device design.

REFERENCES

- [1] Singh, N., Khan, T., Kumar, S., Kanaujia, B. K., Choi, H. C., Kim, K. W., ... & Kishk, A. A., 2024. Ultra-thin flexible rectenna integrated with power management unit for wireless power harvester/charging of smartwatch/wristband. *Scientific Reports*, 14(1), 7447. <https://doi.org/10.1038/s41598-024-40778-5>
- [2] Kumar, R., and Lee, J., 2022. Power management challenges in wearable electronics: A review,” *IEEE Access*, vol. 10, pp. 110345–110360.
- [3] Zhang, X., Liu, Y. and Wang, Z., 2024. Recent advances in skin waste heat energy harvesting wearable flexible thermoelectric devices, *Renewable and Sustainable Energy Reviews*, vol. 202, Art. no. 114719. doi: 10.1016/j.rser.2024.114719
- [4] Van Toan, N., Nguyen, T. D. H. and Park, J., 2021. Flexible and skin-mounted thermoelectric generators for wearable applications, *Applied Energy*, vol. 305, Art. no. 117811. doi: 10.1016/j.apenergy.2021.117811
- [5] Lee, Y.G., Kim, J., Kang, M.S., Baek, S.H., Kim, S.K., Lee, S.M, Kwon, B. (2020). Design and experimental investigation of thermoelectric generators for wearable applications. *Energy Conversion and Management*, 206 112464
- [6] Shen, X., Qi, Y. Yuan, M., 2025. A thermoelectric wristband based on single-walled carbon nanotubes for energy harvesting, *Scientific Reports*, vol. 15, Art. no. 26831. doi: 10.1038/s41598-025-12751-8
- [7] Wang, Y., Liu, H., Zhang S., 2025. Radiation-modulated thermoelectric fabrics for wearable energy harvesting,” *National Science Review*, vol. 12, no. 7, 2025, Art. no. nwaf215. doi: 10.1093/nsr/nwaf215
- [8] Liu, Y., Chen, J. and Wang, P., 2022. Ultra-low power energy harvesting systems: Design and applications,” *IEEE Transactions on Power Electronics*, vol. 37, no. 8, pp. 9876–9890.
- [9] Analog Devices, 2021. “LTC3108: Ultralow Voltage Step-Up Converter and Power Manager,” Datasheet, 2021. [Online]. Available: <https://www.analog.com/media/en/technical-documentation/data-sheets/ltc3108.pdf>
- [10] Rowe, D. M., 2006. *Thermoelectrics handbook: Macro to nano*. CRC Press.
- [11] Liu, J., Zhang, H., & Hu, X. (2016). Wireless power transfer for wearable electronics: Design, performance, and challenges. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 63(10), 1731–1743.
- [12] Horowitz, P., & Hill, W., 2015. *The art of electronics* (3rd ed.). Cambridge University Press.
- [13] Nechibvute, A., Chawanda, A., & Luhanga, P., 2018. Thermal energy harvesting on the bodily surfaces of arms and legs through a wearable thermoelectric generator. *Smart Materials Research*, Article ID 1284562.
- [14] Yu, R., Feng, S., Sun, Q., Xu, H., Jiang, Q., Guo, J., Dai, B., Cui, D., & Wang, K., 2024. Ambient energy harvesters in wearable electronics: fundamentals, methodologies, and applications. *Journal of Nanobiotechnology*, 22, 497. <https://doi.org/10.1186/s12951-024-02774-0>
- [15] Alajmi, A. S. M., Alotaibi, M. A. and Alharbi, H. A. “Energy harvesting analysis of wearable thermoelectric generators integrated with human skin,” *Energy*, vol. 282, 2023, Art. no. 128850. doi: 10.1016/j.energy.2023.128850

- [16] Van Toan, N., Tuoi, T. T. K., Van Hieu, N., & Ono, T., 2021. Thermoelectric generator with a high integration density for portable and wearable self-powered electronic devices. *Energy Conversion and Management*, 245, 114571. <https://doi.org/10.1016/j.enconman.2021.114571>
- [17] Hashim, H. T., 2025. Human body heat harvesting via wearable biomedical sensor generating renewable energy, *International Journal of Heat and Technology*, vol. 43, no. 4, 2025. doi: 10.18280/ijht.430434
- [18] Lee, M. J., Kim, S. and Cho, B. J., 2020. Flexible thermoelectric generators for human body heat harvesting,” *Nano Energy*, vol. 71, Art. no. 104633. doi: 10.1016/j.nanoen.2020.104633
- [19] Khan, M., & Khan, K., 2021. Experimentation of a wearable self-powered jacket harvesting body heat for wearable device applications. *Journal of Cleaner Production*, 312, 127698. <https://doi.org/10.1016/j.jclepro.2021.127698>
- [20] Tohidinejad, M., Rezvani, A., & Sadri, A., 2019. Designing a hybrid energy-efficient harvesting system for head- or wrist-worn healthcare wearable devices. *IEEE Transactions on Biomedical Circuits and Systems*, 13(6), 1344–1353.
- [21] Babu, R., 2016. *Design and development of an inductive power transfer system for charging of battery in wrist watches with metallic back plate* [Master’s thesis, University of Kerala].