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A thermal management system to reuse thermal waste released by high power light emitting diodes (LED)

System zarządzania ciepłem do ponownego wykorzystania ciepła odpadowego wydzielanego przez wysokotężne diody emitujące światło (LED)

***Abstract**. The project addresses the significant challenge posed by the substantial waste heat generated during the operation of high-power LEDs. To tackle this issue, the project proposes a novel solution involving the utilization of a thermoelectric generator (TEG) and a heat exchanger to convert the waste heat into usable energy. By strategically placing a high-power LED on the TEG with an accompanying heatsink for efficient heat dissipation, the system aims to enhance overall energy productivity while mitigating environmental impact. The inclusion of capacitors for voltage stabilization and energy storage, coupled with a boost converter to elevate TEG output to 5V, aligns with the chosen DS18B20 temperature sensor to emphasize energy efficiency. The project's analysis reveals a substantial increase in power generation by cascading five TEGs in series, resulting in a remarkable increment of 236.20% compared to a single TEG. Additionally, the capacitor voltage charge analysis indicates a significant increase of 59.91% for a 2.5V 10F capacitor compare to 2.7V 50F capacitor for 6 minutes duration. These findings underscore the project's efficacy in addressing waste heat challenges and advancing energy reclamation from high-power LED systems.*

***Streszczenie.** Projekt ten odnosi się do znaczącego wyzwania, jakie stanowi znaczna ilość ciepła odpadowego generowanego podczas pracy wysokotężnych diod LED. Aby rozwiązać ten problem, projekt proponuje nowatorskie rozwiązanie polegające na wykorzystaniu generatora termoelektrycznego (TEG) oraz wymiennika ciepła do przekształcenia ciepła odpadowego w użyteczną energię. Poprzez strategiczne umiejscowienie wysokotężnej diody LED na TEG z towarzyszącym radiatorem dla efektywnego odprowadzania ciepła, system ma na celu zwiększenie ogólnej produktywności energetycznej przy jednoczesnym łagodzeniu wpływu na środowisko. Włączenie kondensatorów do stabilizacji napięcia i przechowywania energii, w połączeniu z przetwornicą zwiększającą napięcie wyjściowe TEG do 5V, jest zgodne z wybranym czujnikiem temperatury DS18B20, co podkreśla efektywność energetyczną. Analiza projektu ujawnia znaczny wzrost generacji energii poprzez kaskadowe połączenie pięciu TEG w szereg, co skutkuje wyjątkowym wzrostem o 236,20% w porównaniu do pojedynczego TEG. Dodatkowo, analiza naładowania napięcia kondensatora wskazuje na znaczący wzrost o 59,91% dla kondensatora 2,5V 10F w porównaniu do kondensatora 2,7V 50F przy 6-minutowym czasie trwania. Odkrycia te podkreślają skuteczność projektu w rozwiązywaniu problemów związanych z ciepłem odpadowym oraz postępie w odzyskiwaniu energii z systemów LED o dużej mocy.*

Keywords: high-power light-emitting diodes (LEDs), thermal management system, energy efficiency, waste heat, thermoelectric generator (TEG), heat exchanger, energy productivity
Słowa kluczowe: diody emitujące światło o wysokiej mocy (LED), system zarządzania ciepłem, efektywność energetyczna, ciepło odpadowe, generator termoelektryczny (TEG), wymiennik ciepła, wydajność energetyczna

Introduction

High-power Light Emitting Diodes (LEDs) have gained widespread adoption in various lighting applications due to their remarkable brightness and energy efficiency [1]. However, a notable challenge associated with High-power LEDs is the generation of substantial heat during their operation [2]. This heat can adversely affect the performance and lifespan of the LEDs. To address this issue and optimize the efficiency of High-power LEDs, the development of a sophisticated Thermal Management System is crucial. This system aims to efficiently reuse the thermal waste produced by High-power LEDs, ensuring their sustained performance and contributing to overall energy conservation. High-power LEDs operate at currents exceeding 20mA and are characterized by their luminosity, measured in lumens, as opposed to low-power LEDs, which are typically measured in milli-candelas [1]. The applications of High-power LEDs span a wide range, including automobile lighting and general fixtures, owing to their energy efficiency and durability. A fundamental distinction between High-power and low-power LEDs lies in their brightness, power consumption, and heat generation. While low-power LEDs are suitable for indicators and displays, High-power LEDs produce substantially more light, ranging from 150 to over 1,000 lumens. However, this increased brightness comes at the cost of higher heat generation, necessitating effective thermal management systems to ensure optimal functionality and longevity [1].

Thermoelectric Generators (TEGs) present an innovative solution to harness the excess heat generated by High-power LEDs and convert it into electrical energy [3]. Operating on the Seebeck effect, TEGs utilize semiconductors to create an electric potential difference in response to temperature differentials. This unique capability allows for the efficient conversion of thermal energy into a measurable voltage, offering a sustainable method to repurpose thermal waste for powering other electronic components. To understand the working principle of TEGs, it's essential to grasp the role of p-type and n-type semiconductors in the thermocouple [2], [3], [4]. The Seebeck effect induces a voltage potential proportional to the temperature differential across these semiconductors, facilitating the conversion of heat into electrical power. The historical development of the Seebeck Effect, dating back to

Alessandro Volta's discovery in 1794 and further exploration by Thomas Seebeck in 1821, underscores the long-standing interest and recognition of this phenomenon as a means to generate electricity from temperature differentials [5], [6].

Heatsinks play a pivotal role in the Thermal Management System, efficiently dissipating heat away from electronic components [7]. Constructed from materials with high thermal conductivity, such as aluminum or copper, heatsinks facilitate the gradual transfer of heat away from the source they cool. This is essential for maintaining optimal operating temperatures and ensuring the longevity of electronic devices. The Thermal Management System for High-power LEDs also incorporates buck-boost converters, which maintain the voltage level to meet the demands of electronic systems requiring higher voltage than the available power supply [8]. This ensures that electronic components receive the necessary power for efficient and reliable operation. Temperature sensors, exemplified by the DS18B20, are integral components that convert temperature changes into electrical signals.

These sensors play a crucial role in monitoring and controlling temperature levels, providing a feedback mechanism for the Thermal Management System to maintain optimal operating conditions. Recent advances in thermal management systems focus on innovative solutions to enhance the performance and sustainability of LED technology. Waste heat recovery using thermoelectric generators (TEGs) has witnessed significant advancements in addressing the challenges of managing thermal waste from high-power LEDs. Experimental studies with LED car lights demonstrated the conversion of thermal energy into electricity using TEGs, showcasing the potential for creating independent power sources for LEDs, especially in automotive applications [9].

The optimization of TEGs for industrial environments led to improved output power and conversion efficiency, addressing challenges associated with industrial waste heat recovery [10]. Another innovative study introduced the use of alternate triboelectric charges to enhance TEG output voltage and power. This novel technique provides a potential solution to the low output power and efficiency challenges faced by traditional TEG systems [11]. These studies highlight continuous efforts to innovate and overcome limitations in TEG technology, offering promising avenues for efficient and sustainable waste heat recovery in high-power LED applications. The field of thermal management for high-power LEDs has witnessed significant strides, with studies proposing novel techniques and systems to address inherent challenges. Heat pipe-assisted TEGs have been proposed for industrial waste heat recovery, confirming their feasibility and effectiveness in waste heat recovery and electricity conversion [12].

Comprehensive approaches combining thermoelectric coolers (TECs) and microchannel heat sinks for high-power LEDs showcased favorable thermal management performance, especially in high ambient temperature conditions [13]. Copper wick-based Loop Heat Pipes have been explored for thermal management of high-power LED modules, providing insights into their effectiveness in controlling LED reliability and performance [14]. The development of a comprehensive Thermal Management System for reusing thermal waste from High- power LEDs is imperative for enhancing energy efficiency and sustainability. The integration of TEGs, heatsinks, boost converters, and temperature sensors forms a holistic solution to efficiently manage the heat generated by High-power LEDs, contributing to the overall success of energy-efficient lighting solutions.

Methodology

The selection of a 60W switching power supply is a choice, delivering not only the necessary power capacity but also a variable output voltage (11V~14VDC) that can be accurately calibrated to meet the optimal working voltage of the chosen 10W High Power LED. This flexibility guarantees dependable operation and economical use of power in the lighting system. The thermal arrangement technique as shown in Figure 1 makes use of the LED's special ability to function at temperatures higher than 100 degrees Celsius. Thermoelectric generators (TEGs) may absorb surplus heat and convert it into useful energy by placing the LED on top of them. Concurrently, the residual heat is released and dissipated by a heatsink beneath the TEG, avoiding overheating and aiding in the efficient thermal control of the system as a whole.

The connection of numerous TEGs in series as shown in Figure 2 is a deliberate move aimed at maximising the overall output voltage of the system. When individual TEG voltages are insufficient for a given application, this serial connection method helps by producing a cumulative voltage that satisfies the needs of external loads or devices. It discusses the difference between parallel and series connections, with parallel connections emphasising maximising current output and series connections concentrating on higher voltage. Next part of the process is choosing the right heatsink, which requires extensive testing of 5 models as shown in Figure 3 to determine which is best for heat dissipation. The primary

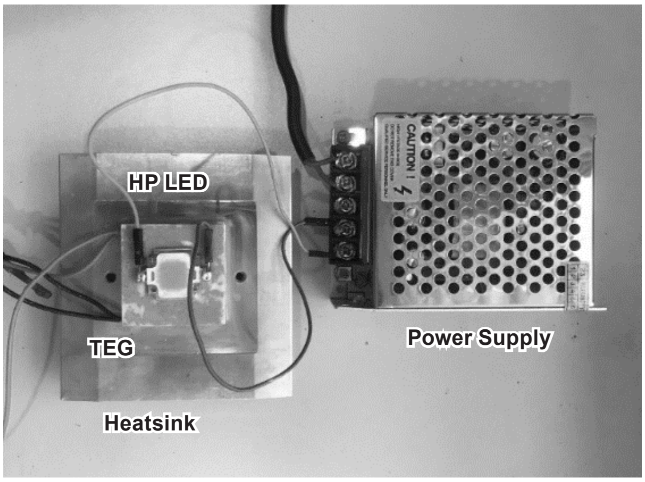


Figure 1: Energy Harvesting Part

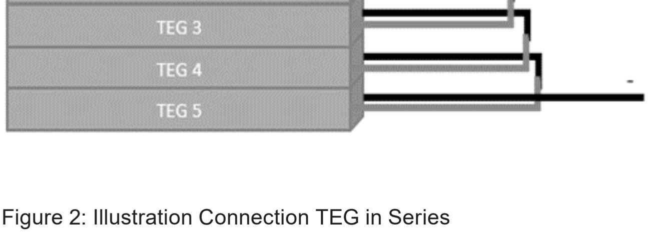


Figure 2: Illustration Connection TEG in Series

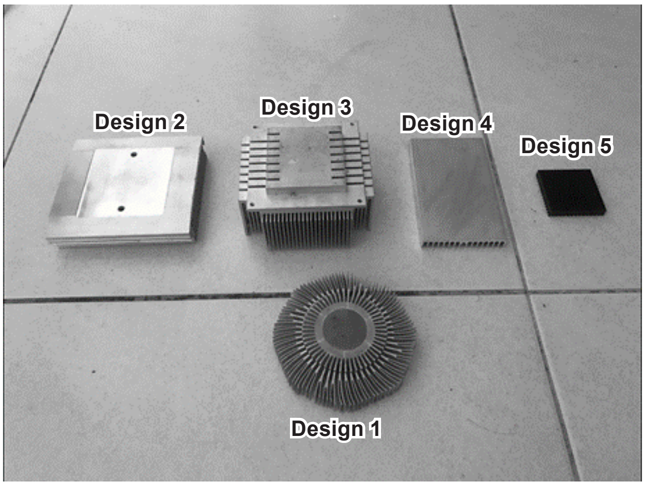


Figure 3: 4 Types of Heatsink

objective is to boost the thermoelectric generator's (TEG) temperature differential between its hot and cool sides. This temperature difference, also known as the thermal gradient, is a factor influencing the efficiency of TEGs. The heatsink plays a role in dissipating the heat from the TEG. By testing multiple heatsink types, it is essentially evaluating their thermal performance and heat dissipation capabilities. The goal is to identify a heatsink that can efficiently draw heat away from the TEG, thereby maintaining a substantial temperature difference between the hot and cold sides. A larger temperature difference is desirable for TEGs because it directly correlates with the voltage output.

According Figure 4,capacitors are strategically used to manage power variability and stabilise output voltage. Capacitors serve as smoothing elements, reducing abrupt variations brought on by temperature swings to produce a steady and steady voltage output. Additionally, capacitors function as energy storage devices, releasing stored energy during intervals of reduced power generation and acting as a buffer during periods of higher power generation. This dual function ensures a steady and balanced power flow to support linked components, which adds to the system's overall stability.

The use of the boost converter is for improving the TEG's comparatively low output. The chosen boost converter raises the TEG's output to a steady 5V within its 0.6V to 5V output range, which is in line with the functional needs of electronic parts such as the DS18B20 temperature sensor. Because of the careful component selection and integration, the system works effectively as a whole, producing electrical power from waste heat while retaining stability and adaptability. The coding process follows the same pattern; the Arduino Uno microcontroller was selected due to its ease of use and compatibility with the DS18B20 temperature sensor. The Dallas Temperature Control Library is used by the Arduino code to connect with the sensor, offering a convenient platform for creating and testing electronic devices. In order to provide an organised framework for temperature monitoring, the code handles necessary tasks such as library inclusions, pin configurations, object instantiation, device address setup, setup functions, reporting temperature functions, and loop functions.As presented in Figure 5 the project's specifications are well-met by the selected waterproof temperature sensor, the DS18B20, which has a low current consumption and operates within the given input voltage range. The boost converter ensures compatibility and energy efficiency by increasing the TEG's output to the voltage required by the sensor.

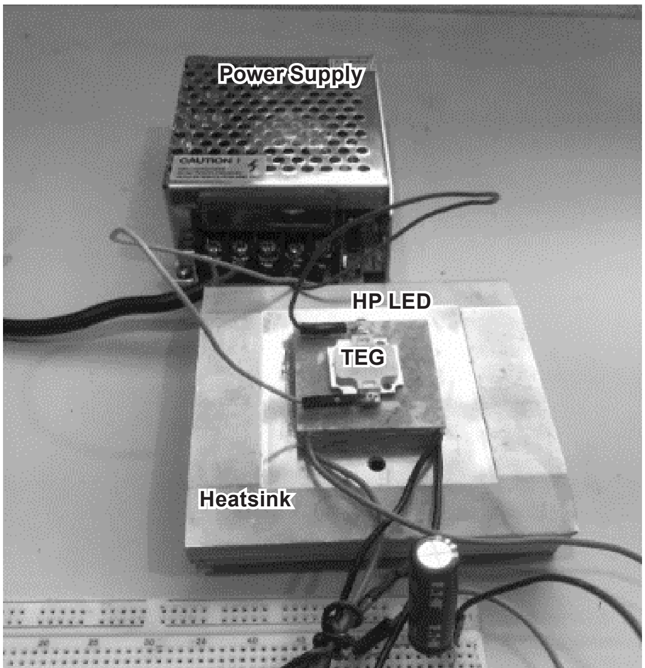


Figure 4: TEG Output Connected with Capacitors for Energy Storage

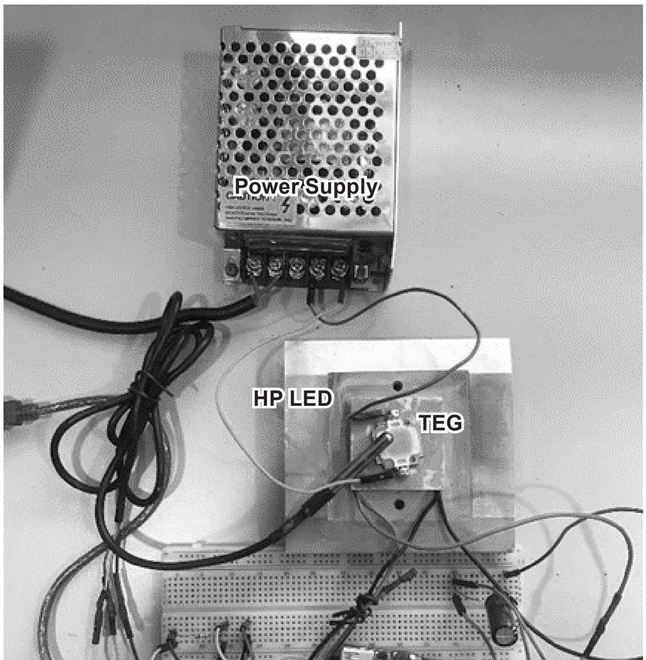
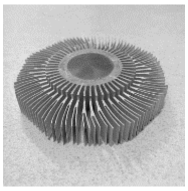
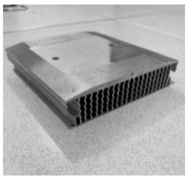
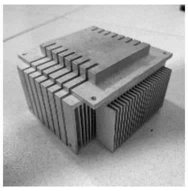
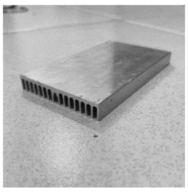
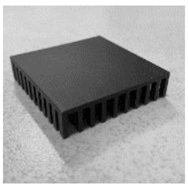


Figure 5: Temperature monitoring by Temperature Sensor

Results, Analysis and Discussion

This chapter focuses on presenting the results obtained from the methodology. The process of choosing a suitable heat sink for the project entails giving careful thought to important elements such size, fin design, and material conductivity. The main objective is to effectively control the heat produced by high-power LEDs so that they function within safe temperature ranges. Prioritizing material conductivity means that materials with high thermal conductivity – which enable efficient heat transfer – are preferred. Choosing the best fin design is essential if you want to maximize the surface area for better heat dissipation. Another important consideration is the heat sink's size, which needs to be carefully chosen to meet the system's unique thermal needs. Performance statistics, based on the output voltage from two Thermoelectric Generators (TEGs) over a 15-minute period, are shown for five different heatsink designs in Table 1. Distinctive features impacting heat dissipation and TEG performance are reflected in every design. The output voltage of Design 1 increases gradually, indicating steady but modest heat dissipation. On the other hand, Design 2 is clearly the most effective; it reaches 1 V after 15 minutes, demonstrating excellent heat control. Design 3 has output voltages that are constantly high, suggesting that effective heat dissipation can continue. The efficacy of Designs 4 and 5 varies, with Design 5 standing out as it rises at 10 and 15 minutes. The m performance gain as a result of the heatsink designs is graphically represented by the graph in Figure 6. The greater effectiveness of heat sink type 2 in regulating temperature variations is demonstrated by the consistently higher TEG output voltage during the 15-minute duration. Multiple analyses support the choice, confirming heat sink type 2's superior and consistent performance in preserving the TEG and related components' ideal operating conditions.

Table I: TEG Output According to Different Heatsink Design

Times (Min)	Output 2 TEG (V)	Size	Design Heatsink
5	0.633	90 mm × 85 mm × 18 mm	 Design 1
10	0.73		
15	0.745		
5	0.955	100 mm × 95 mm × 21 mm	 Design 2
10	0.97		
15	1		
5	0.964	92 mm × 92 mm × 53 mm	 Design 3
10	0.95		
15	0.97		
5	0.74	100 mm × 59 mm × 9 mm	 Design 4
10	0.75		
15	0.75		
5	0.741	40 mm x 40 mm x 10mm	 Design 5
10	0.837		
15	0.874		

The analysis of TEGs in flat and cascade configurations is covered in detail in next part. The cascade configuration connects several TEGs in series, offering benefits including the sum of voltages produced by individual TEGs, which significantly increases the total voltage output. Increased power generation efficiency is another benefit of this configuration, particularly when there are significant temperature differences along the cascade. The usefulness of cascading TEGs in Figure 7 for increased power generation is highlighted by the data in Table 2 and the accompanying graphs plotted in Figure 8, which show a positive correlation between the total number of connected TEGs in a cascade arrangement and the overall output voltage. s. The increment percentages between TEG 1 and TEG 5 for 30-minute duration is (742−221)/(221) /100 = 235.7%. Thus, it shows that the TEG 5 voltage output has improved compare to the single TEG.

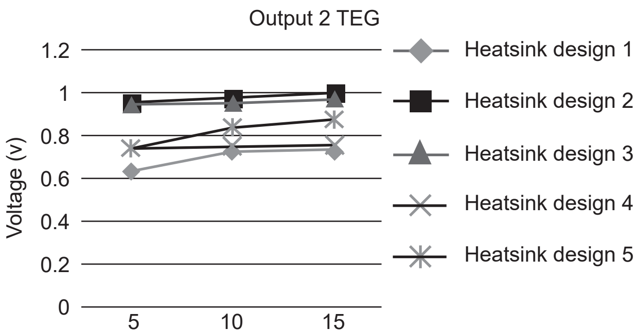


Figure 6: The graph shows the increase according to the performance heatsink

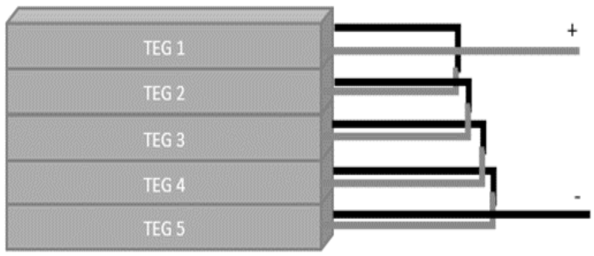


Figure 7: Illustration Connection of TEG in Cascade Arrangement

On the other hand, the flat configuration of TEGs, illustrated in Figures 9 and Table 3, prompts questions regarding the sensitivity of efficiency to temperature gradients. The in-

Table 2: TEG Output According to The Total Number of TEG

Times (Min)	1 TEG (mV)	2 TEG (mV)	3 TEG (mV)	4 TEG (mV)	5 TEG (mV)
5	222	410	534	622	718
10	226	415	529	664	738
15	223	409	534	655	741
20	220	408	527	641	734
25	218	412	536	646	740
30	221	400	531	631	742

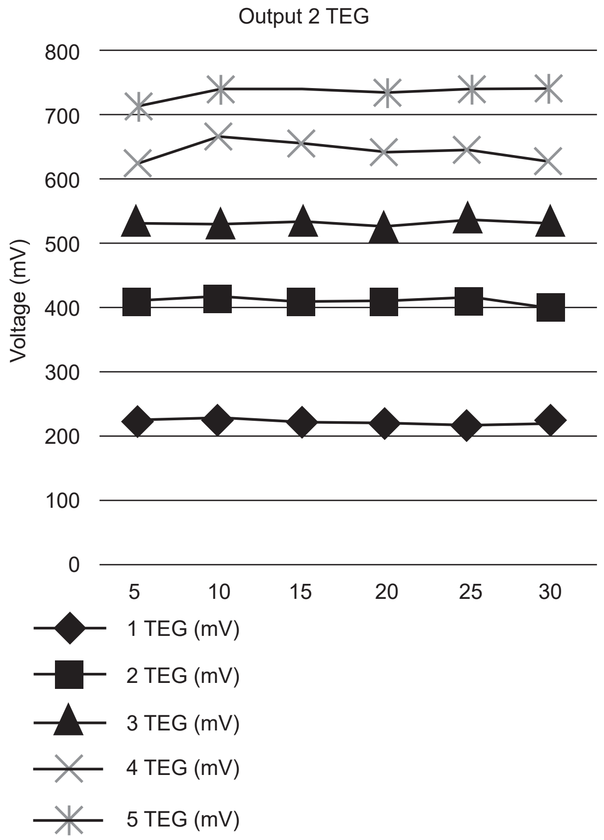


Figure 8: Graph Shows Increase in TEG Output with Total TEG

crement percentages for the Output of 3 TEG between 5 minutes and 30 minutes is (197−314)/(314) ×100 = −0.37%. The percentage is negative at 30 minutes, indicating a decrease

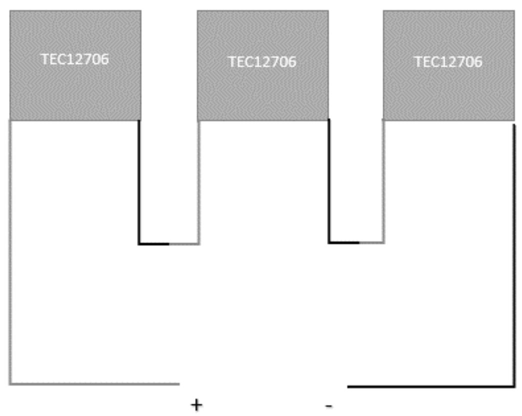


Figure 9: Illustration Connection TEG in Flat Arrangement

in value compared to the initial value at 5 minutes. Heat dissipation, thermal equilibrium, or other external factors altering the temperature gradient are the likely causes of the TEG output drop shown in graph Figure 10 with time. In order to maximize power generation in a flat configuration, it is necessary to maintain a stable and advantageous temperature gradient while taking into account variables that could eventually affect the surrounding environment.

Table 3: TEG Output According to 3 HP LED and 3 TEG

Times (Min)	Output 3 TEG (mV)
5	314
10	385
15	361
20	250
25	233
30	197

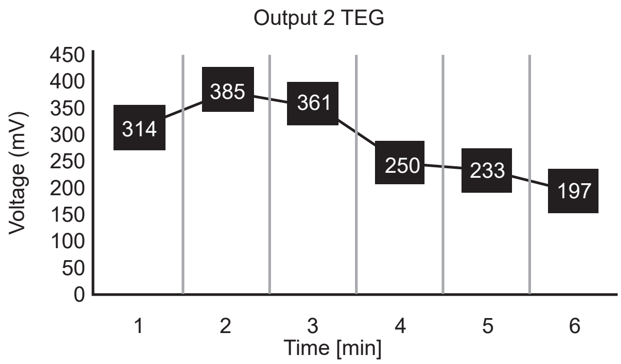


Figure 10: Graph Shows Decline in TEG Output with increasing time

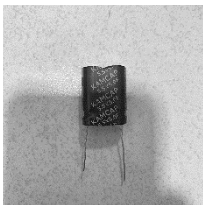
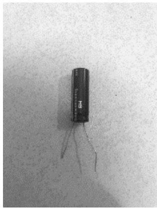
Other section focuses on energy storage using capacitors. The provided data in Table 4 and the graph in Figure 11 illustrate the increase in capacitor voltage charge over time for three different capacitor types. Higher capacitance capacitors demonstrate a slower rate of voltage increase, while higher voltage ratings allow capacitors to handle higher voltages without failure. The increment percentages between 2.7V 50F and 2.5V 10F for 6-minutes duration is (1119−701)/(701) x 100 = 59.91%. The analysis reveals the impact of varying capacitance and voltage ratings on the charging behavior of capacitor. The discharge process of the capacitor during periods when the energy source is inactive is explained, emphasizing its role as a temporary energy reservoir that contributes to continuous power supply and the reliability of connected components.

Finally, temperature readings at room temperature and after being heated with a lighter are as shown in Figure 12 and Figure 13 demonstrate the system's capacity for temperature detection. These values emphasize the system's capacity to recognize and react to changes in external conditions by displaying its dynamic reaction to temperature variations.

Conclusion

This project stands as a successful endeavor in tackling the challenges associated with thermoelectric energy harvesting from high-power LEDs, adopting a comprehensive thermal management approach. The incorporation of a strategically selected 10W LED, designed to operate efficiently at elevated temperatures, lays a solid foundation for effec-

Table 4: Capacitor Voltage Charge Increase within minutes

Times (Min)	Voltage Charge (mV)	Types Capacitor
1	180	 2.7V 50F
2	299	
3	403	
4	519	
5	610	
6	701	
1	782	 5.5V 5F
2	981	
3	1059	
4	1095	
5	1103	
6	1119	
1	265	 2.5V 10F
2	729	
3	918	
4	981	
5	1015	
6	1033	

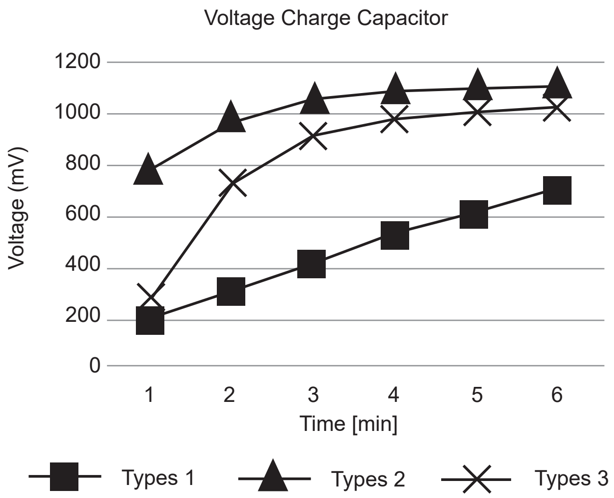


Figure 11: The graph increases in capacitor charge

tive energy extraction. The implementation of a cascading arrangement of TEGs in series, marked by an impressive 235.7% increment in output voltage between TEG 1 and TEG 5 over a 30-minute duration, underscores the project's commitment to optimizing energy harvesting efficiency. Rigorous testing and analysis of heatsink designs, with Design 2 exhibiting a notable 1V output at 15 minutes, further contribute to the system's thermal performance.

Additionally, the integration of capacitors, with a substantial 59.91% increment in voltage charge between the highest and lowest rated capacitors, plays role in stabilizing voltage and ensuring a consistent power supply. The use of a boost

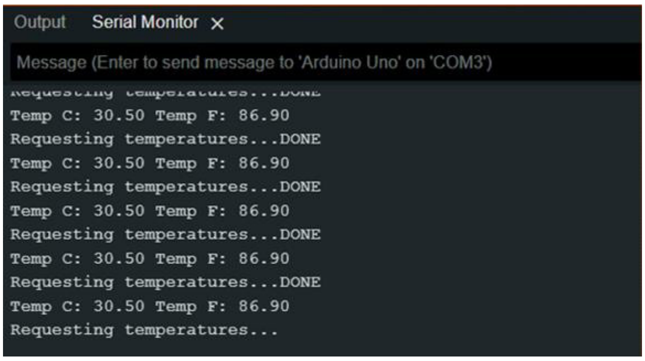


Figure 12: Room Temperature Reading

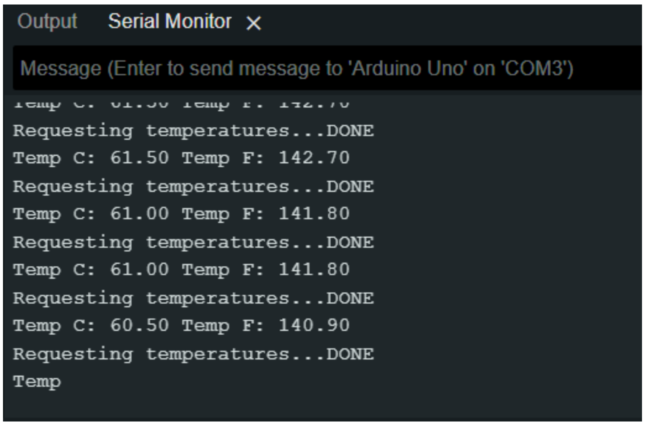


Figure 13: Temperature Reading When Heated with a Lighter

converter to address low TEG output reflects a proactive approach to enhancing system performance. Furthermore, the inclusion of a temperature sensor, as evidenced by incremental readings at room temperature and dynamic responses to external heat sources, enhances the system's reliability in monitoring temperature variations. Real-world applicability is emphasized through the incorporation of a waterproof DS18B20 and a smart control system, highlighting the project's consideration of practical deployment scenarios. Looking forward, the project envisions potential enhancements, such as alternative TEG configurations and integration with renewable sources, demonstrating a forward-looking perspective. The increment percentages serve as concrete indicators of the quantifiable improvements achieved in various aspects of the project, positioning it as a valuable contribution to the practical advancement of thermoelectric energy harvesting systems

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