

## **Experimental Performance Evaluation of an Asphalt Pavement Thermoelectric Harvesting System Under Tropical Weather Conditions**

**Dean Cruise Edwin<sup>1</sup>, Aimie Nazmin Azmi<sup>1\*</sup>, Mohan Lal Kolhe**

<sup>1</sup> *Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia*

<sup>2</sup> *Faculty of Engineering & Science, University of Agder, PO Box 422, NO 4604 Kristiansand, Norway*

*\*Correspondence: [aimienazmin@utem.edu.my](mailto:aimienazmin@utem.edu.my)*

### **Abstract**

This study experimentally evaluates a thermoelectric harvesting system designed to utilize thermal gradients in asphalt pavement under tropical weather conditions. The prototype combines a solid heat-transfer mechanism using copper bars with a water-based cooling system to maintain a temperature difference across TEC1-12706 thermoelectric modules. Field measurements were conducted from 08:00 to 18:00 under sunny, rainy, and cloudy conditions, with pavement temperature, cooling-water temperature, and TEG voltage output recorded hourly. The results show that the voltage response was influenced by the thermal gradient established across the system. Among the evaluated weather conditions, sunny weather produced the largest temperature difference and highest measured voltage output, reaching 20.1 °C and 0.29 V, respectively. Rainy conditions produced smaller and more variable responses, while cloudy conditions exhibited intermediate behavior. The findings demonstrate the feasibility of generating measurable thermoelectric voltage from asphalt pavement thermal gradients and highlight the importance of environmental conditions and thermal management in determining system performance.

**Keywords:** Asphalt Pavement; Thermoelectric Generator; Energy Harvesting; Temperature Gradient; Tropical Weather

### **Introduction**

The increasing demand for sustainable energy technologies has encouraged the development of alternative approaches for recovering energy from sources that would otherwise remain unused. In tropical regions, asphalt pavements are continuously

exposed to solar radiation and can accumulate substantial amounts of thermal energy during daytime conditions. The relatively high heat absorption and storage capacity of asphalt can contribute to elevated pavement surface temperatures and the urban heat island effect, while also representing a potential source of recoverable thermal energy.[1], [4]

Several technologies have been investigated for harvesting energy from pavement infrastructure, including photovoltaic, piezoelectric, and thermoelectric systems. Among these approaches, thermoelectric generators (TEGs) offer the advantage of directly converting a temperature difference into electrical voltage through the Seebeck effect without requiring moving mechanical components [2], [7]. For pavement applications, a temperature gradient can be established between the heated pavement surface and a cooler medium, allowing the thermal energy stored within the pavement to produce a measurable electrical response [1], [4].

Previous studies have investigated different configurations for thermoelectric energy harvesting from asphalt pavement, including solid heat-transfer structures and liquid-based thermal management systems [1], [3]–[5]. Solid systems typically employ thermally conductive materials to transfer heat from the pavement to the hot side of the thermoelectric module, whereas liquid-based systems use a circulating fluid to assist heat transfer or cooling. The performance of either configuration is strongly dependent on maintaining an adequate temperature difference across the thermoelectric modules.

Despite the potential of pavement-based thermoelectric harvesting, its performance is inherently influenced by environmental conditions. Variations in solar exposure and weather conditions affect pavement temperature and consequently the thermal gradient available to the thermoelectric system. This issue is particularly relevant in tropical environments, where sunny, cloudy, and rainy conditions may occur within relatively short periods. Experimental evaluation under different weather conditions is therefore necessary to understand the practical response of thermoelectric pavement systems [1], [3]–[5].

This study experimentally evaluates a hybrid thermoelectric harvesting system for asphalt pavement under tropical weather conditions. The proposed prototype combines copper bars for solid heat transfer with a water-based cooling system to establish a temperature difference across TEC1-12706 thermoelectric modules. Field measurements were conducted under sunny, rainy, and cloudy conditions, and the resulting pavement temperature, cooling-water temperature, temperature difference, and TEG voltage output were evaluated. The study specifically examines how variations in the thermal gradient under different weather conditions influence the measured voltage response of the proposed system.

## **Thermoelectric Energy Harvesting Principles**

### *2.1 Thermoelectric Module Principle*

Thermoelectric generators (TEGs) are solid-state devices that directly convert a temperature difference into electrical voltage through the Seebeck effect [2]. When the two sides of a thermoelectric module are maintained at different temperatures, a voltage is generated across the module. The generated voltage can be expressed as:

$$V = \alpha(T_h - T_c) \quad (1)$$

$V$  : Voltage of TEG  
 $\alpha$  : Seebeck coefficient  
 $T_h$  : Hot side temperature  
 $T_c$  : Cold side temperature

A thermoelectric module consists of multiple p-type and n-type semiconductor elements connected electrically in series and thermally in parallel. The magnitude of the generated voltage therefore depends strongly on the temperature difference,  $\Delta T$ , established across the module [2], [7]. Maintaining an effective thermal gradient between the hot and cold sides is consequently an important consideration in thermoelectric energy harvesting systems.

In pavement applications, heat absorbed by the asphalt can provide the hot-side thermal input, while an appropriate cooling mechanism maintains a lower temperature on the opposite side of the TEG. The resulting temperature gradient enables a measurable electrical voltage to be generated.

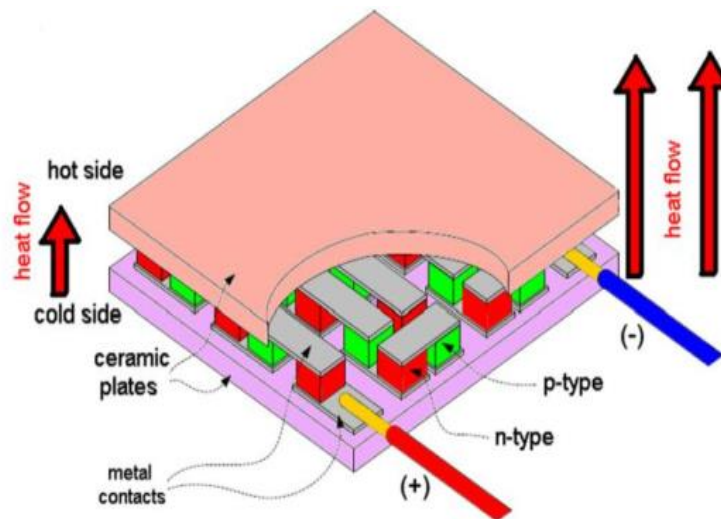


**Figure 1:** Basic operating principle of a thermoelectric generator

## 2.2 Solid System Harvesting Thermoelectric Energy on Asphalt Pavement

Solid-based thermoelectric pavement systems use thermally conductive components to transfer heat from the asphalt pavement to the hot side of the TEG. Conductive materials such as copper plates or heat-conduction elements can be embedded within the pavement to improve heat transfer, while a heat sink or other cooling arrangement maintains the cold side of the module. Previous field investigations have demonstrated the feasibility of this configuration for converting pavement thermal gradients into electrical energy [1], [3], [5]. A representative solid-system configuration is shown in Figure 2.

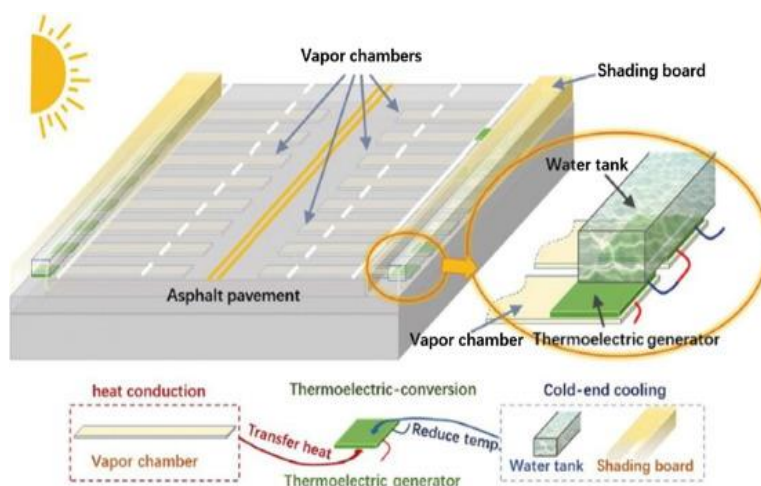
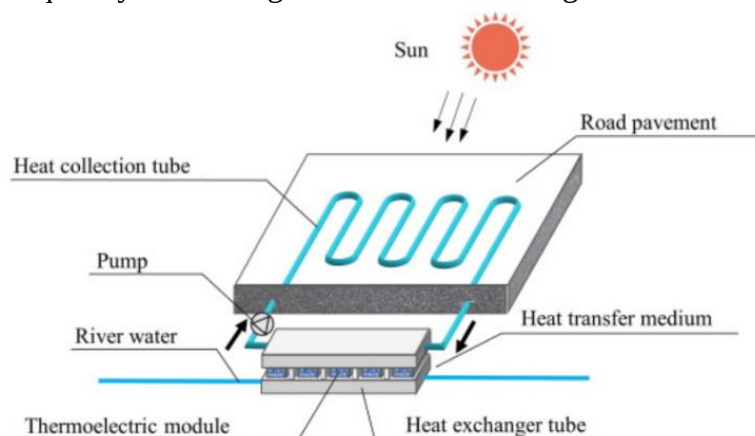


**Figure 2:** Representative solid-system configuration [4]

### 2.3 Liquid System Harvesting Thermoelectric Energy on Asphalt Pavement

Liquid-based systems employ a circulating fluid to assist heat transfer or thermal management within the pavement system [4]. Pipes or cooling channels can be integrated with the pavement or thermoelectric assembly to transfer heat and maintain the temperature gradient required for thermoelectric generation. Compared with a purely solid heat-transfer arrangement, the use of a circulating fluid provides an additional mechanism for controlling the cold-side temperature of the TEG. A representative liquid-system configuration is shown in Figure 3.



**.Figure 3:** Representative liquid-system configuration

## Concept and Design

### 3.1 Prototype Design

The proposed thermoelectric pavement prototype combines solid heat transfer with liquid-based cooling to establish a temperature difference across the thermoelectric modules. As illustrated in Figure 4, copper bars embedded in the asphalt pavement model transfer heat from the pavement towards the hot side of the TEC1-12706

thermoelectric modules. On the opposite side, aluminium cooling blocks connected to a water-circulation system provide cooling to maintain the thermal gradient across the modules.

The cooling system consists of a water tank, a 5 V DC water pump, plastic tubing, and aluminium cooling blocks. Water is circulated through the cooling system to remove heat from the cold side of the thermoelectric modules. Copper was selected as the solid heat-transfer medium because of its high thermal conductivity. The main components and dimensions of the prototype are summarized in Table 1.

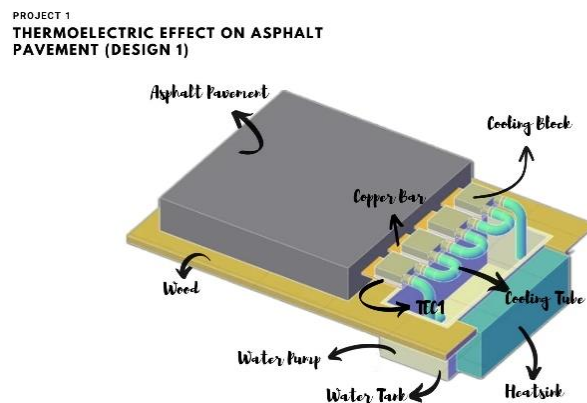


**Figure 4:** Configuration of the proposed thermoelectric asphalt pavement prototype.

**Table 1**

| No. | Item                       | Specification                                                  |
|-----|----------------------------|----------------------------------------------------------------|
| 01  | Thermoelectric (TE) Module | TEC1-12706 (40mmx40mm)                                         |
| 02  | Cooling tube               | Made up from plastic                                           |
| 03  | Asphalt Pavement Model     | Cold mix asphalt type layer (175mm x 180mm x 60mm)             |
| 04  | Cooling block              | Made up from aluminium (40mm x 40mm)                           |
| 05  | Copper Bar                 | Made up from copper (250mm x 25mm)                             |
| 06  | Water tank                 | Made up from Acrylic (160mm x 90mm x 125mm with 1mm thickness) |
| 07  | Heatsink                   | Made up from aluminium (69mm x 36mm x 120mm)                   |
| 08  | Coolant Liquid             | Water                                                          |
| 09  | Water pump                 | 5V DC motor water pump                                         |

### 3.2 System Operation

The operating principle of the proposed system is illustrated in Figure 5. Solar exposure heats the asphalt pavement, and the absorbed thermal energy is transferred

through the embedded copper bars towards the hot side of the thermoelectric modules. Simultaneously, the water-circulation system removes heat from the opposite side through the aluminium cooling blocks. The resulting temperature difference between the hot and cold sides of the thermoelectric modules produces a voltage through the Seebeck effect.

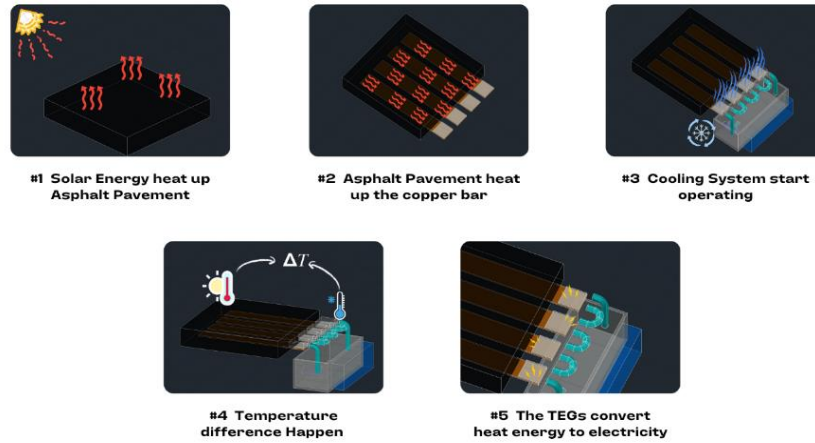


**Figure 5:** Operating principle of the proposed thermoelectric pavement system

### 3.3 Experimental Procedure and Data Collection

Field measurements were conducted at the UTeM Library under three weather conditions: sunny, rainy, and cloudy. Measurements were recorded hourly from 08:00 to 18:00. The asphalt pavement and cooling-water temperatures were measured using an infrared thermometer, while the TEG voltage output was measured using a digital multimeter.

For each measurement, the temperature difference between the asphalt pavement and cooling water was calculated as:

$$\text{Temperature Difference, } \Delta T = T_p - T_w \quad (2)$$

$T_p$  : Pavement Temperature

$T_w$  : Water Temperature

The measured temperatures, calculated temperature differences, and TEG voltage outputs were subsequently compared to evaluate the response of the prototype under different weather conditions.

### Results and Discussion

Based on the methodology described in the previous section, the experimental results are presented and discussed in terms of temperature behaviour under varying weather conditions and the relationship between temperature difference and measured TEG voltage output. Field measurements were conducted between October 2024 and January 2025 under sunny, rainy, and cloudy weather conditions.

#### 4.1 Temperature Testing Under Varying Weather Conditions

Figure 6 shows the pavement temperature, cooling-water temperature, and corresponding temperature difference under sunny conditions on 9 January 2025. The pavement temperature increased substantially from the morning, reaching its highest values during the early afternoon before decreasing towards the evening. The cooling-water temperature increased more gradually throughout the day. Consequently, the temperature difference between the pavement and cooling water increased during the morning and remained relatively high during the early afternoon. The maximum temperature difference of 20.1 °C was recorded at 13:00. After 14:00, the temperature difference progressively decreased as the pavement temperature declined towards the evening.

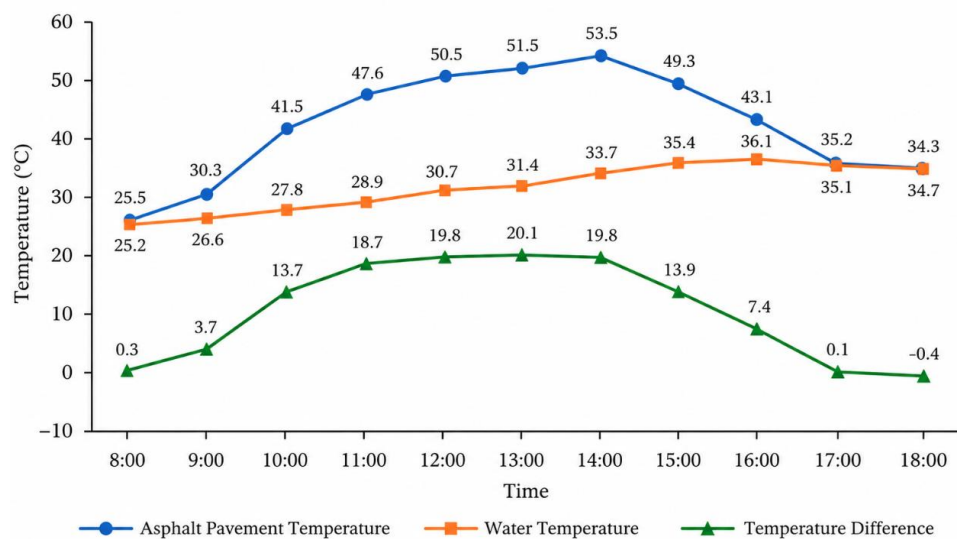


**Figure 6:** Temperature Behavior Under Sunny Weather on 9 January 2025

**Figure 7:** shows the pavement temperature, cooling-water temperature, and corresponding temperature difference under rainy conditions on 23 December 2024.

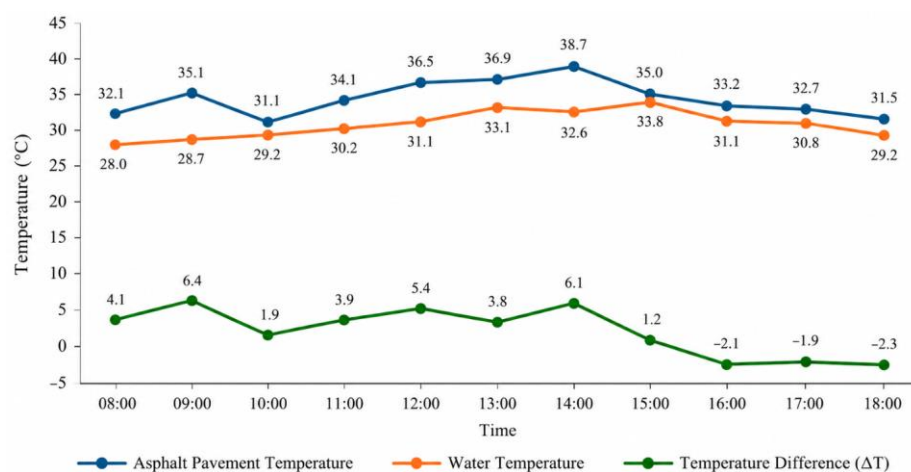


**Figure 7:** Temperature Behavior Under Rainy Weather on 23 December 2024

Under rainy conditions, the pavement temperature showed greater fluctuations than under sunny conditions. The pavement temperature increased from 32.1 °C at 08:00 to 35.1 °C at 09:00, before decreasing to 31.1 °C at 10:00. It subsequently increased and reached a maximum of 38.7 °C at 14:00 before decreasing towards the evening. The cooling-water temperature varied more gradually, increasing from 28.0 °C at 08:00 to a maximum of 33.8 °C at 15:00 before decreasing thereafter. Consequently, the temperature difference remained relatively small and variable throughout the measurement period. The temperature difference became negative from 16:00 onwards, indicating that the cooling-water temperature exceeded the pavement temperature during the late afternoon.

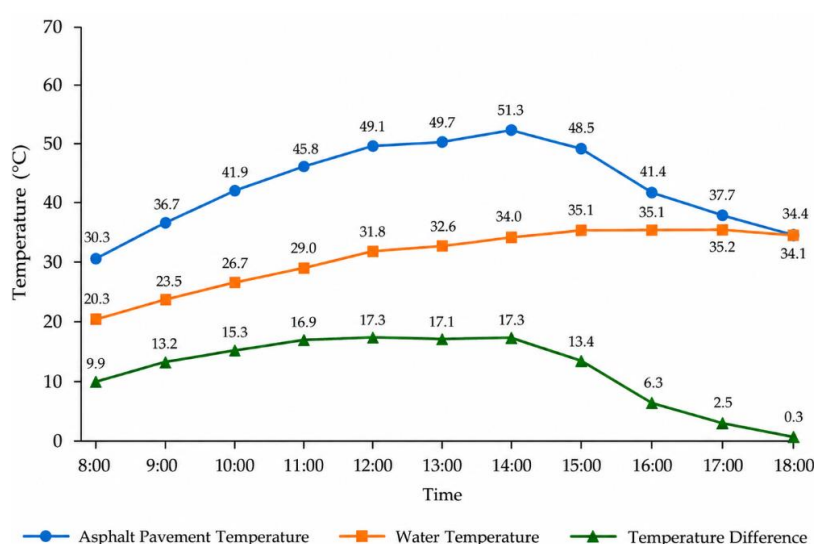


**Figure 8:** Pavement temperature, cooling-water temperature, and temperature difference under cloudy conditions on 6 January 2025

Under cloudy conditions, both pavement and water temperatures generally increased from the morning to the afternoon before decreasing towards the evening, as shown in Figure 8. The pavement temperature remained higher than the cooling-water temperature throughout most of the measurement period, maintaining a positive temperature difference during daytime conditions. The temperature difference subsequently decreased as the pavement cooled towards the evening. Compared with sunny conditions, the cloudy condition generally produced a smaller thermal gradient, indicating the influence of weather conditions on the thermal behavior of the system.

#### 4.2 Effect of Temperature Difference on TEG Voltage Output under Varying Weather Conditions

Figures 9-11 illustrate the relationship between the temperature difference and the measured TEG voltage output under sunny, rainy, and cloudy weather conditions, respectively. In general, higher temperature differences were associated with higher voltage outputs, while reductions in the temperature difference towards the late

afternoon were accompanied by lower voltage outputs. Under some conditions, reversal of the temperature gradient was also associated with a change in voltage polarity. These observations demonstrate that the electrical response of the TEG system was influenced by the thermal gradient established between the pavement and cooling sides of the system.

Among the tested conditions, sunny weather generally produced the largest temperature differences and higher voltage outputs, whereas rainy conditions resulted in smaller and more variable responses. Cloudy conditions showed intermediate behavior. The results therefore indicate that weather-dependent thermal conditions play an important role in determining the voltage-generation performance of the proposed asphalt pavement thermoelectric system.

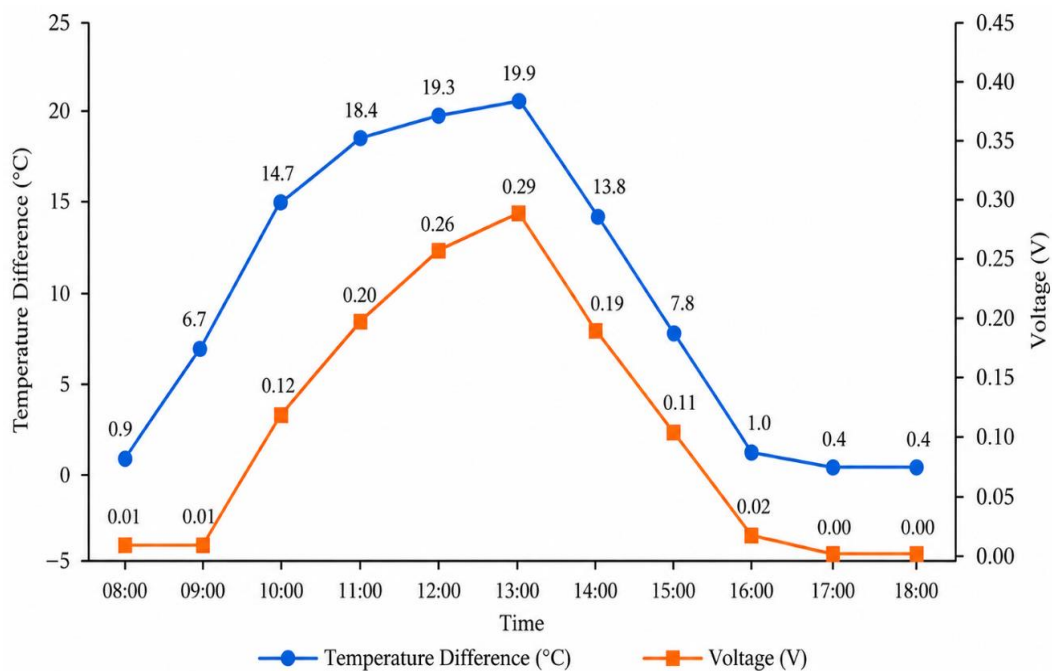


**Figure 9:** Relationship Between Temperature Difference and Voltage Across Time (9 January 2025)

Figure 9 shows the relationship between temperature difference and TEG voltage output under sunny conditions on 9 January 2025. Both parameters generally increased during the morning and reached their highest observed values during the early afternoon before decreasing towards the evening. Although some deviations between the temperature-difference and voltage trends were observed, larger thermal gradients were generally associated with larger voltage outputs. This indicates that the voltage response of the TEG system was influenced by the thermal gradient established across the system.

Figure 10 shows the relationship between temperature difference and TEG voltage output under rainy conditions on 23 December 2024. Both parameters exhibited greater fluctuations than under sunny conditions, reflecting the more variable thermal

conditions during the measurement period. The temperature difference decreased substantially during the late afternoon and eventually became negative.

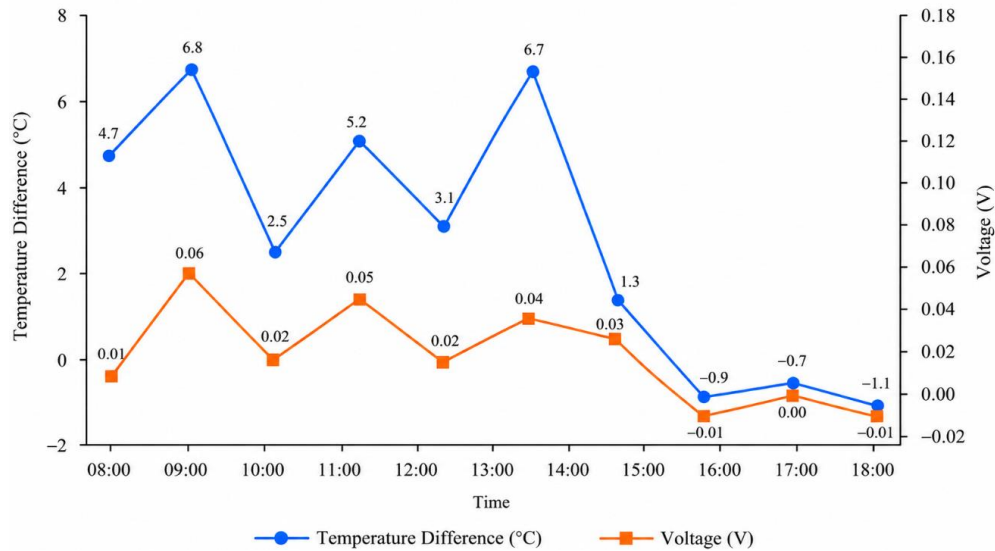


**Figure 10:** Relationship Between Temperature Difference and Voltage Across Time (23 December 2024)

A corresponding change in voltage polarity was also observed, with negative voltage values recorded towards the end of the measurement period. These results demonstrate the influence of changing thermal conditions on the voltage response of the TEG system during rainy weather.

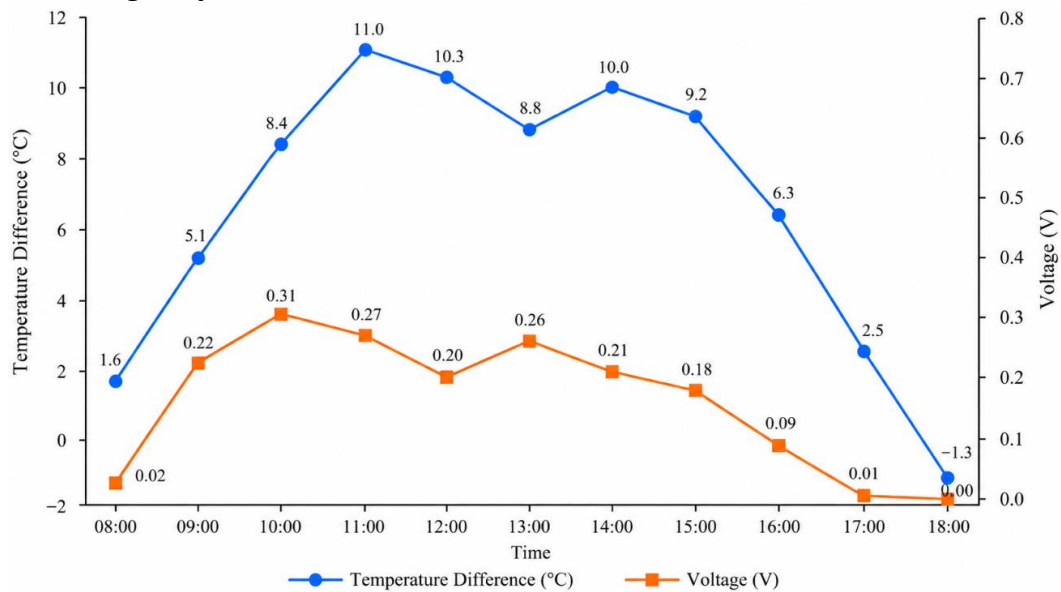


**Figure 11:** Relationship Between Temperature Difference and Voltage Across Time (6 January 2025)

Figure 11 shows the relationship between temperature difference and TEG voltage output under cloudy weather conditions on 6 January 2025. Both parameters generally increased during the morning before decreasing towards the evening. Although the voltage response did not follow the temperature difference proportionally at every measurement point, larger temperature differences were generally associated with larger voltage outputs. Towards the late afternoon, both the temperature difference and voltage output decreased substantially, with the temperature difference becoming negative by the end of the measurement period.

Overall, the three weather conditions produced distinct thermoelectric responses. Sunny weather produced the largest observed temperature difference and the highest measured voltage output, while rainy conditions resulted in generally smaller and more variable responses. Cloudy conditions exhibited intermediate behavior. These findings indicate that the electrical response of the proposed system is strongly influenced by the thermal gradient developed between the pavement and cooling sides of the thermoelectric modules.

## Conclusion

This study experimentally evaluated a thermoelectric harvesting system designed to utilize thermal energy from asphalt pavement under tropical weather conditions. Field measurements under sunny, rainy, and cloudy conditions demonstrated that the measured TEG voltage output was influenced by the thermal gradient established between the pavement and cooling sides of the system. Among the tested conditions, sunny weather produced the largest temperature difference and the highest measured voltage output, reaching 20.1 °C and 0.29 V, respectively.

The results demonstrate the feasibility of generating measurable thermoelectric voltage from asphalt pavement thermal gradients and highlight the importance of environmental conditions and thermal management in system performance. Further work should investigate improved thermal coupling, passive or more energy-efficient cooling strategies, optimized thermoelectric module configurations, and longer-term field testing. Electrical load characterization and larger-scale experiments are also required to reliably assess the practical power and energy harvesting potential of the proposed system.

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