
PERFORMANCE EVALUATION OF A PROTOTYPE THERMO-ELECTRIC GENERATOR (TEG) BASED ENERGY HARVESTER FROM ASPHALT PAVEMENTS

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Asphalt pavements trap a substantial amount of solar radiation and comprise between 30% and 45% of urban areas, thus contributing to the urban heat island (UHI) effect due to their high thermal storage, which leads to the softening and degradation of the pavement. Energy harvesting techniques are one of the promising ways to mitigate these effects while making sustainable use of the trapped thermal energy. In this study, the performance of a thermoelectric generator (TEG)-based energy harvesting prototype integrated with asphalt pavements was evaluated. A fabricated 30 × 30 cm asphalt slab with a thickness of 5 cm and an embedded copper collector was used. The hot side of the TEG module was attached to the L-shaped copper collector, and the cold side was connected to a water-filled aluminium heat sink. Six TEG modules were mounted for redundancy, of which four were active during data collection. Performance was evaluated under controlled indoor conditions; temperatures were measured using embedded thermocouples and electrical output was measured using a multi-meter. Under controlled indoor conditions, temperature differences (ΔT) of 12–22°C produced 0.295–0.897 V, 3.6–15.73 mA, and a maximum power output of 14.12mW from the four active TEG modules, confirming the feasibility of harvesting thermal energy from asphalt pavements. This corresponds to a potential of approximately 157 mW/m² of asphalt pavement surface. The study demonstrates a practical approach to pavement-based thermoelectric energy harvesting in hot-climate regions and recommends outdoor field testing, seasonal performance monitoring, and optimization for large-scale deployment in Kano, Northern Nigeria.

Keywords: Heat Sink; Seebeck Effect; Thermal Collector; Conveyor; Asphalt Pavement

1. INTRODUCTION

Asphalt pavement, a black body surface, absorbs solar radiation, elevating its temperature, often reaching 25–50°C depending on location and weather (Aletba et al., 2021). In tropical regions with high solar exposure, this heat, combined with heavy traffic, can melt the asphalt, causing surface defects like bumps and bruises upon cooling. To ensure durability, especially in tropical areas, maintaining lower asphalt temperatures is crucial. The absorbed solar radiation converts to thermal energy, heating the asphalt above the ambient temperature and subsequently releasing heat to the environment, contributing to the Urban Heat Island effect (UHI) (Nuruzzaman, 2015). Cooling asphalt is essential to mitigate the UHI effect and enhance pavement longevity, considering its substantial coverage in urban areas (30 to 45% of land area).

Pavements, comprising 30% to 45% of urban areas, significantly contribute to the urban heat island (UHI) effect due to their high thermal storage and low solar radiation reflection (Ikechukwu, 2015; Kuehl, 2021). Traditional cooling methods involve applying reflective coatings on the surface to deflect rather than absorb solar radiation. Aletba et al. (2021) emphasize the importance of cooling strategies for pavement surfaces, considering their direct exposure to solar impact, influenced by surface characteristics like colour, material, shape, and roughness. Utilizing high-albedo and high emissivity surfaces minimizes heat retention and lowers pavement temperatures. Similarly, engineering materials and pavement layers with low thermal conductivity and high heat capacity can reduce thermal diffusivity, combatting the heat emitted by asphalt pavement.

Energy harvesting refers to the process of capturing and converting ambient or waste energy from the environment, such as solar, thermal, kinetic, or wind energy, into usable electrical power for

operating devices or systems. Energy harvesting can be a useful technology as it offers to mitigate the urban heat island (UHI) effect, prolong the lifespan of asphalt pavements and use the harvested heat in many useful applications. Thermal energy from incident solar radiation which is absorbed by the asphalt pavement can be harvested using energy harvesting technologies such as; the photovoltaic solar panel, heat pipe solar collector and thermoelectric generator systems.

Research on energy harvesting from asphalt pavement using Thermoelectric Generators (TEGs) is an emerging area of interest with promising potential. TEGs embedded in asphalt pavement can potentially convert the heat generated by solar radiation and vehicular traffic into electrical energy, allowing for energy harvesting and power generation from roadways. Various researchers (Mona et al. (2021); Sharuddin (2021); Jiang et al. (2017); Datta et al. (2017); Tahami and Dessouky (2021)) have developed TEGs for harvesting energy from asphalt pavements. Over the years researchers have focused on increasing the TEGs operational efficiency through optimizing the thermoelectric material (Yang et al. (2017) and Lobunets (2021)); Enhancing heat transfer in the asphalt pavement (Alhamdo (2023); Qusay Doraghi (2024); Liu (2012); and Leon (2010)); Improving System design and configuration (Eman (2018); Maduabuchi (2021)) and Heat sink optimization (Jiang et al. (2017); Boonyasri et al. (2016)). Performance of these prototype systems depends on the climatic conditions in the region and the properties of the asphalt itself. Thus, to properly utilize this technology in Nigeria, there is the need to quantify the potential of this technology for potential applications in powering road equipment such as traffic lights, road signs, and similar low-power devices.

2. METHODOLOGY

2.1 Experimental Material/Equipment

The following material and equipment were used in this research.

- The prototype TEG Energy Harvesting system
- TA612C Thermometer (Data Logger)
- Non-contact Infrared Thermometer
- K-Type Thermocouples
- DT9205A Digital Multimeter
- KM-SPM-11 Solar Power Meter (Solarimeter)

2.2 The Prototype Asphalt TEG based Energy Harvesting System

Figure 1 presents the picture of the prototype TEG energy harvester. The prototype consists of:

- Asphalt pavement with embedded collector: A hot mix asphalt pavement, consisting of 47% coarse aggregates, 40% fine aggregates, 7% mineral filler (cement) and 6% bitumen with a surface area of 900 cm² (30 × 30 cm) and thickness of 5 cm. A copper plate is embedded into the asphalt pavement.
- Collector and conveyor: The collector and conveyor assembly was fabricated from an L-shaped copper plate. The TEG modules (SP1848-27145) with dimension of 40 mm by 40mm each and with voltage and current output of 0.97V, 225mA at 20° temperature difference. Six modules were physically mounted on the collector for redundancy (Figure 1c), of which four were wired in and active for the data collection reported in this study, so that the system could continue operating on the remaining modules in the event of an individual module failure.
- Heat sink: The heat sink was fabricated from aluminium sheets
- Wooden box housing: A wooden housing box was constructed to encase the prototype. This facilitated ease of movement and served as a protective cover, shielding the heat sink from direct solar radiation.

2.3 Experimental Setup

The conveyor section (L-shaped side of the copper plate) embedded within the asphalt pavement was connected to the hot side of the thermoelectric (TEG) module (figure 2). The cold side of the TEG module was attached to the aluminium heat sink, with both interfaces enhanced using thermal paste and secured by mechanical fastening.

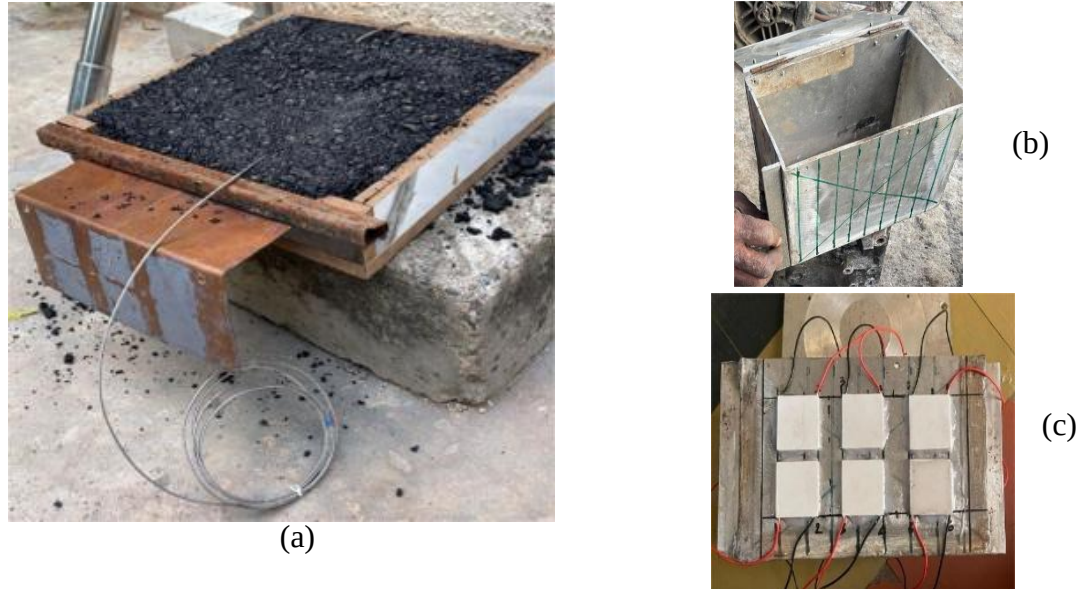


Figure 1: The prototype Asphalt TEG based energy Harvesting system (a) the Pavement (b) Heat Sink (c) TEGs attached to the Heat Sink

To minimize undesired heat losses, an insulation layer was placed between the conveyor and the heat sink, and additional insulation material was used to cover the exterior surface of the copper collector. The insulation was put to minimise heat losses from the asphalt not the sink. For temperature measurements, four K-type thermocouples were strategically installed: one embedded in the asphalt pavement in direct contact with the copper plate (collector), another attached to the conveyor, a third placed inside the heat sink, and a fourth positioned in open air near the prototype to record the ambient temperature. These provided continuous readings of temperature distribution across the system. The entire assembly was mounted within a wooden box, which served both as a protective casing and as a portable frame to facilitate movement and handling of the prototype.



Figure 2: The prototype set-up for testing

2.4 Experiment Procedure and Data Analysis Technique

- Instrumentation: Four K-type thermocouples were connected to the TA612C data logger as shown in Figure 3. The DT9205A digital multi-meter was connected directly across (for

voltage) and in series with (for current) the series-connected TEGs, so the effective electrical load during measurement was the multimeter's own internal resistance rather than a discrete external load resistor. The KM-SPM-11 solarimeter was used to measure lamp intensity.

- Procedure: The 500W halogen lamp was positioned 25 cm above the asphalt surface. The data logger, multi-meter, and solarimeter were initialized. The lamp was switched on, and data (temperature, voltage, current, light intensity) was recorded at 5-minute intervals for a period of 2 hours. The digital multi meter internal resistance and the connecting wires served as the load resistance.



Figure 3: Experimental Set-up

- Data Analysis Technique: The raw data was processed using Microsoft Excel. The high-frequency data from the logger (recorded every second) was sorted and averaged into 5-minute intervals to align with the experimental procedure. Duplicate entries were removed. Electrical power (in mW) was calculated using the formula $P = V * I$. Relationships between parameters (e.g., temperature difference vs. power, solar intensity vs. power) were established and visualized using Excel charts.

3. RESULTS AND DISCUSSION

Figure 4 and 5 present the temperature and power profiles recorded during the highest-output indoor test run, illustrating the general shape of the system's thermal and electrical response over the test period. The lamp intensity varied between 1295 and 1980 W/m², which caused a progressive rise in surface temperatures. The collector temperature increased from 40.7 °C to a maximum of 63.3 °C, while the conveyor temperature ranged from 32.6 °C to 45.8 °C. The heat sink remained relatively stable within 26–35 °C, reflecting the effectiveness of the insulation layer placed between the conveyor and the heat sink (Section 2.3) in limiting undesired heat transfer to the cold side. This produced a maximum temperature difference (ΔT) of approximately 22°C between the conveyor and the heat sink in this run, with voltage rising to 0.897 V, current to 15.73 mA, and power reaching a peak of 14.12 mW at 17:50 hrs, coinciding with the peak temperature difference.

These measured outputs are considerably lower than the TEG module's rated performance of 0.97 V and 225 mA at a 20 °C temperature difference (Section 2.2). This gap is attributed to several factors. First, voltage and current were measured directly with the DT9205A digital multi-meter rather than across a resistive load matched to the TEG's internal resistance, which limits the current the module can deliver into the measurement circuit. Second, thermal contact resistance at the collector–TEG and TEG–heat sink interfaces, despite the use of thermal paste, reduces the effective temperature difference across the TEG junctions relative to the temperature difference measured between the copper collector and the heat sink. Third, connecting the modules in series means that any underperforming module limits the current of the entire array. Insulation losses around the collector

and conveyor further reduce the temperature differential actually available to the modules relative to idealized datasheet test conditions.

The performance of the thermoelectric generator (TEG)-based asphalt pavement energy harvester was evaluated under indoor test conditions, focusing on the temperature difference (ΔT) between the conveyor and the heat sink (T_3-T_4), and the resulting voltage, current, and power output. Averaged across the indoor test replicates, the ΔT ranged between 12 °C and 22°C, producing 0.295–0.897 V, 3.6–15.73 mA, and a maximum power output of 14.12 mW combined from the four active TEG modules. Scaling this average output over the 900 cm² (0.09 m²) slab (asphalt) area used in the prototype ($14.12 \text{ mW} \div 0.09 \text{ m}^2$) gives a harvestable potential of approximately 157 mW/m² of asphalt pavement surface under similar indoor conditions. These results are broadly consistent with those of Datta et al. (2017), who reported a system-level (aggregate) output of 0.52–0.68 V and about 15mW at similar ΔT values (10–15°C); both figures represent total system output rather than a per-module value, making the comparison directly comparable. The slight difference may be attributed to variations in module contact resistance and heat transfer efficiency. Both studies confirm a direct proportionality between ΔT and output power, validating the Seebeck principle.

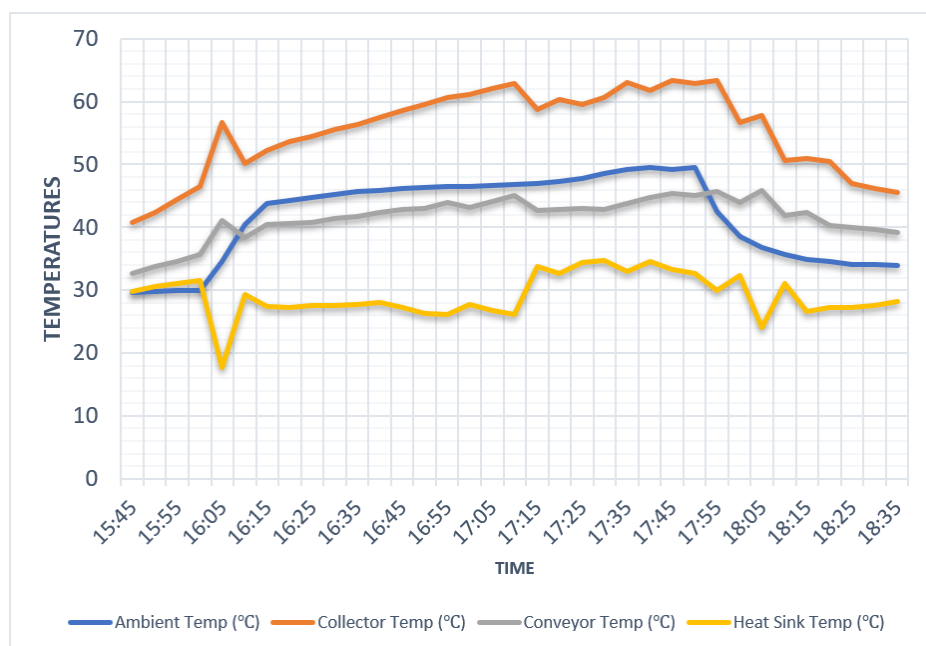


Figure 4: Temperature profile recorded during the highest-output indoor test run

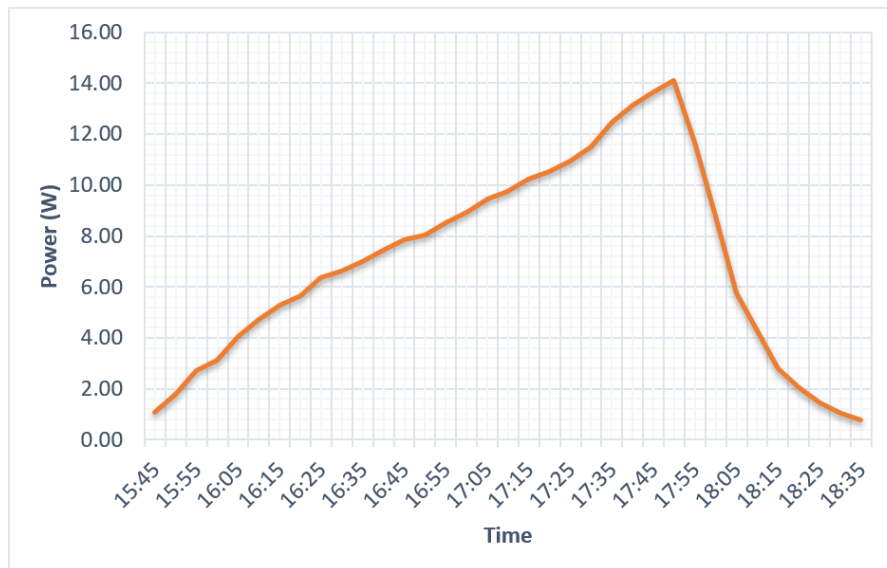


Figure 5: Power output recorded during the highest-output indoor test run

4. CONCLUSION

The design demonstrated technical feasibility for harvesting low-grade thermal energy from asphalt pavements. The completed prototype was tested under laboratory conditions, where simulated solar radiation produced stable electrical outputs, with a maximum indoor power output of 14.12 mW combined from the four active TEG modules, recorded during the highest-output trial, consistent with related studies such as Datta et al. (2017). For context, these output levels are comparable to the power budgets of several classes of low-power roadside electronics: commercial low-power wireless sensor nodes typically draw on the order of 3–12 mW during active operation (for example, the Crossbow MICAz draws approximately 2.8 mW and the Intel IMote2 approximately 12 mW (Raj & Steingart, 2018), and a single low-power LED indicator draws on the order of several milliwatts. This suggests that, while the harvested power is insufficient to continuously supply conventional road electrical systems such as full traffic signal heads, it is within range of intermittently duty-cycled sensor nodes or indicator LEDs when paired with an energy storage buffer such as a supercapacitor or small battery. Comparative analysis showed that system performance is strongly influenced by temperature gradient, ambient conditions, and material thermal properties. Although the harvested power is insufficient to independently supply conventional road electrical systems, the results demonstrate the system's viability as a supplementary energy source when integrated with hybrid renewable systems and energy storage. The next step is to test the prototype under real outdoor conditions in Kano, Northern Nigeria and to explore load-matched circuitry to help close the gap between the modules' rated and measured performance.

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