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# REVIEW ON THE PERFORMANCE ENHANCEMENT METHODS IN THERMO-ELECTRIC GENERATOR (TEG) BASED ENERGY HARVESTERS FROM ASPHALT PAVEMENTS

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## ABSTRACT

*Asphalt pavements receive a lot of solar radiation from the sun, which is converted into thermal energy in the pavement, leading to the heating and softening of the pavement material, thus affecting its longevity. Also, in urban areas where these pavements form up to 40% of the land area, it leads to a phenomenon called the urban heat island (UHI). Thermoelectric generators (TEGs) can convert the thermal energy in the pavement into useful electrical energy for other applications, thus preventing these effects and also being a source of energy. The use of TEGs has the potential of solving these problems, and researchers have been working on developing TEGs for energy harvesting from asphalt pavements. The reported efficiencies of these systems are very low, and there is a need for improving the efficiency and power density of these devices. Thus, this paper firstly provides the details of the technology for energy harvesting from pavements and also provides an up-to-date review of the various strategies that are employed in improving the performance of the TEGs in asphalt pavements. These strategies include improving the thermoelectric properties of the TEG module or material; enhancing the thermal conductivity within the asphalt pavement; TEG system design and optimization; and increasing the temperature difference between the hot and cold sides by employing a well-designed heat sink. All these performance enhancement methods were found to improve the performance of the TEG system. The reported efficiencies of TEG systems embedded in asphalt pavements are still below 10%, and thus there is a need to improve the efficiencies. Additionally, most of these studies are either numerical or tested in laboratory prototypes.*

Keywords: *Asphalt Pavement: Heat Sink: Urban Heat Island: Energy Harvesting: Seebeck Effect:*

## 1. INTRODUCTION

Asphalt pavement refers to any hard surface that is covered in asphalt, like a road or a driveway. Asphalt, also known as bitumen, is a sticky, black, highly viscous form of petroleum. Its viscous character is used as a binding agent in asphalt-based pavements. The asphalt pavement mixture consists of 90-95% aggregate and sand and 5-10% of asphalt or bitumen (Kuehl, 2021). The viscosity of the asphalt binds the material that make up the asphalt, at the same time making it flexible. The flexibility of the asphalt is a critical feature in the strength of an asphalt pavement, allowing the surface to adjust to varying weather condition and the constantly changing surface beneath it. Another vital quality of asphalt is the ability to repel water from the surface, as water on asphalt pavement surface can cause defects, such as potholes, which are dangerous to vehicles and can also lead to weaker surface beneath the asphalt pavement.

Due to varying weather conditions and different applications, several varieties of asphalts are used to fit various requirements. Roads that are expose to heavy traffic with heavy vehicles, noise control, weather conditions, various pressure and temperature fluctuation etc. require different grades of asphalt that could withstand the pressure from heavy traffic, be flexible enough to avoid cracking due to temperature variations, be porous to avoid retaining water especially in areas with high rainfall. In-order to achieve complete durability, a fully compacted good workable mixture of asphalt is required during application. Asphalt pavement being a black body surface absorbs the radiation from the sun, which results to increase of temperature of the pavement. The temperature of pavement surface may reach 25°C - 50°C depending on geographical location and weather condition (Salam Rodha, 2021). As the temperature increases, the asphalt surface becomes more flexible due to its viscous nature. In tropical areas where solar radiation is high, it can be a crucial threat to the longevity of the asphalt pavement. High temperature along with traffic or heavy vehicles can cause defects to the asphalt pavement by melting it, which could form bumps and bruises at the surface when the temperature decreases. This thus means that for asphalt pavements to be durable especially in the tropics there is the need to keep their temperatures at lower levels. Solar radiation received by pavements is converted into thermal energy thus increasing the temperature of the asphalt pavement above the ambient temperature leading to the release of heat to the environment causing the temperature of the environment to be hotter. Due to the large area covered by asphalt pavement in urban areas (between 30 to 45% of the land area), the effect can be detrimental and causes discomfort to the city dwellers. This is one of the numerous factors that causes the temperature at the heart or the centre of the city to be higher than its surroundings or the suburban area. The phenomena is called Urban Heat Island (UHI) effect (Nuruzzaman., 2015) (Ikechukwu, 2015). Therefore, cooling asphalt pavement is immensely required to reduce to UHI effect and simultaneously increase the longevity of the asphalt pavement. The conventional techniques used for cooling asphalt pavement are by coating the surface with reflective materials which will reflect the incident solar radiation instead of absorbing it. Salam Rodha (2021) reveals the cooling strategies that deals with the pavement surface are important due to its direct incident solar effect, which depends on surface colour, material, shape and roughness. By using high-albedo and high emissivity surface, the pavement can store less heat and lower the surface temperature. These results can also be achieved by designing the materials and pavement layers with low thermal conductivity and high specific heat capacity to reduce thermal diffusivity and pavement temperature and thus combat the heat radiated by asphalt pavement.

Other approaches to combat the effect of high temperatures in asphalt pavements is by the conversion (Energy Harvesting) of the thermal energy in the pavement into other useful forms of energy for applications such as heating, powering of traffic lights, sensors, street lights e.t.c Energy Harvesting can be a useful technique that can mitigate the urban heat island (UHI) effect, prolong the lifespan of asphalt pavements and use the harvested heat in many useful applications.

Various energy harvesting technologies can be used to harvest different kind of energies such as mechanical energy, chemical energy, sound energy, thermal energy etc. (Chetto, 2016 and Elahi, 2022). 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.

The most appropriate technology that can be employed for the harvesting of the thermal energy from the pavement is the use of thermoelectric generators (TEGs) which converts the thermal energy into electrical energy for use in powering devices. TEGs can be embedded within the asphalt pavement to absorb the heat from incident solar radiation and be used for powering road devices thereby utilizing the thermal energy of the pavement and thus preventing asphalt pavement deformation and urban heat island (UHI) effect.

Over the years researchers have focus on the development and testing of TEGs for energy harvesting from asphalt pavements. Notable review in this subject in include Salam Rodha (2021), who presented a review on the various cooling strategies that have been employed in the literature including the use of TEGs. Pascual-Munoz (2013) presented a review on Solar thermal collectors for application in the cooling of asphalt pavement in which the focus was on the utilisation of the thermal energy for other nearby applications such as snow melting, space heating of nearby buildings e.t.c. Jaziri (2020) presented a comprehensive review on the use of thermoelectric generators (TEGs) for different application. There is thus the need to have a detailed review on the up-to-date researches and status of the use of Thermoelectric Generators (TEG) for Thermal Energy Harvesting from Asphalt pavements. The main aim of this review is to provide a comprehensive overview of the performance enhancement methods employed in thermoelectric generators (TEGs) used in asphalt pavements for energy harvesting. This was done by first giving a detail description of the various technologies and principles behind energy harvesting from asphalt pavements using TEGs and then to review the various strategies that are employed to improve the performance of TEG systems in asphalt pavements.

## 2. THEORETICAL FUNDAMENTALS

### 2.1 THE SEEBECK EFFECT

A thermoelectric generator (TEG) system is a device that converts heat energy directly into electrical energy using the Seebeck effect, a phenomenon discovered by Thomas Johann Seebeck in 1821. The Seebeck effect occurs when there is temperature difference across two dissimilar materials an electric voltage is generated, as shown in fig. 1. The voltage developed is given in equation 1.

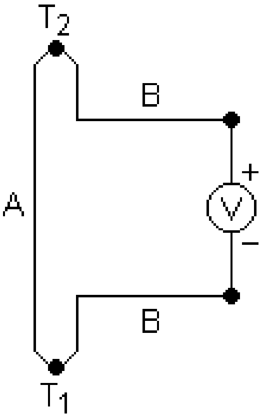

Fig 1: The Seebeck Effect

$$V = \int_{TI}^{T2} \big(S_B(T) - S_A(T)\big)dT \qquad (1)$$

Where:

$S_A$ and $S_B$ are the Seebeck coefficients (also called thermoelectric power or thermopower) of the metals A and B as a function of temperature.

$T_1$ and $T_2$ are the temperatures of the two junctions.

The Seebeck coefficient is non-linear function of temperature, and depend on the conductors' absolute temperature, material, and molecular structure. The Seebeck coefficient, also known as the thermoelectric power, measures the voltage generated per unit temperature difference across the material. It is expressed in microvolts per degree Kelvin (μV/K) or millivolts per degree Kelvin (mV/K). A high absolute value of the Seebeck coefficient is desirable for efficient energy conversion.

If the Seebeck coefficients are effectively constant for the measured temperature range, equation 1 can be approximated as:

$$V = (S_B - S_A).(T_2 - T_1) \qquad (2)$$

### 2.2 TEG SYSTEM

Figure 2 presents the various component of a TEG system which basically consist of: Heating Source (in this case the collector embedded in the asphalt pavement), The TEG module and The Heat Sink

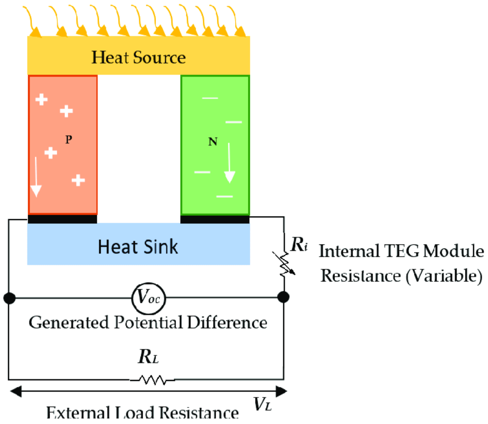

Fig. 2: TEG System

#### 2.2.1 HEAT SOURCE

The heat source is the part of the system that provides the temperature difference required for the Seebeck effect to take place. It can be a heat exchanger, a hot plate, an incident solar radiation, a combustion chamber, or any other source of heat, such as waste heat from industrial processes, internal combustion engines, or even body heat in wearable devices.

#### 2.2.2 TEG MODULE

The heart of a thermoelectric generator is the thermoelectric material or thermoelectric semiconductor. This material is typically made from a combination of n-type and p-type semiconductor materials, which have different electron conductivity properties. When a temperature gradient is applied across the material, electrons diffuse from the hot side (high temperature) to the cold side (low temperature), creating an electric potential difference or voltage. The TEG modules is specified based on the Thermoelectric figure of merit (ZT) which quantifies the efficiency of the TEG module as shown in equation 3.

$$ZT = \frac{S^2 \sigma T}{\kappa} \qquad (3)$$

where

T is the absolute temperature.

S is the Seebeck Coefficient which defines the voltage generated per unit temperature difference expressed in V/K

σ is the electrical conductivity

k is the thermal conductivity

The ranges for the ZT values vary from Low-ZT range (0-0.5), Medium-ZT range (0.5-1.5), High-ZT range (1.5-3). Higher ZT values indicate higher efficiency in converting heat to electricity. The temperature range over which the thermoelectric material can efficiently generate electricity is essential for its practical application. Some materials may be suitable for low-temperature applications, while others can handle high-temperature environments.

The efficiency of a thermoelectric generator (TEG) module refers to its ability to convert heat energy into electrical energy. The efficiency of a TEG module can be calculated using equation 4:

$$\eta = {(ZT * \Delta T)}\Big/{(\Delta T + 1)} \qquad (4)$$

where:

ZT is the thermoelectric figure of merit of the material used in the TEG module.

ΔT is the temperature difference across the TEG module.

### 2.2.3 MATERIALS USED IN TEG MODULE

There are basically two types of TEG modules: The Unicouple and Bicouple. Bicouple is the most widely used TEG module. Bicouple TEG modules utilize two different types of thermoelectric materials, namely n-type (negative) and p-type (positive) semiconductors, to enhance the efficiency of converting heat into electricity. The combination of these two materials creates a thermoelectric couple that exploits the Seebeck effect to generate an electric potential in response to a temperature gradient. The most common materials used for n-type and p-type thermoelectric elements in bicouple TEGs are:

- Bismuth Telluride (Bi2Te3): One of the most widely used thermoelectric materials, especially in moderate temperature ranges (typically between -50°C to 250°C).
- Lead Telluride (PbTe): Suitable for high-temperature applications (typically above 300°C).
- Half-Heusler Alloys (e.g., HfNiSn, ZrNiSn): These materials exhibit good thermoelectric properties and are being extensively researched for higher temperature applications. Half-Heusler alloys typically have thermal conductivities in the range of 10 to 20 W/m·K at room temperature. These materials are being studied for their potential in higher temperature applications.
- 
- Skutterudites (e.g., CoSb3): These complex compounds exhibit good thermoelectric properties, especially at high temperatures. The thermal conductivity of skutterudites can vary widely based on composition and doping. At room temperature, the thermal conductivity can range from about 1 to 5 W/m·K or higher.

### 2.2.4 HEAT SINK

The heat sink is used on the cold side of the thermoelectric material to dissipate the heat absorbed from the hot side. It helps maintain the temperature gradient across the thermoelectric

### 2.3 ASPHALT PAVEMENTS

Asphalt pavement is composed primarily of mineral aggregates, such as sand, gravel, and crushed stone, bound together with asphalt cement, a semi-solid form of petroleum. There are several types of asphalt pavement, each designed to suit specific applications and requirements (figure 3):

i. Hot Mix Asphalt (HMA): HMA is the most common type of asphalt pavement. It is made by heating asphalt binder and mixing it with aggregates (such as sand, gravel, or crushed stone) at a high temperature. HMA is versatile and can be used for a wide range of applications, including highways, local roads, parking lots, and airport runways.

ii. Warm Mix Asphalt (WMA): WMA is similar to HMA but produced at lower temperatures, typically between 50°C and 100°C (122°F to 212°F). It is considered more environmentally friendly because it reduces energy consumption and greenhouse gas emissions during production. WMA is suitable for various road types.

iii. Cold Mix Asphalt: Cold mix asphalt does not require heating during production, making it more convenient for small-scale repairs and patching. It is typically used for temporary or low-traffic roads and as a patching material for

Fig 3: a) Hot Mix Asphalt b) Warm Mix Asphalt c) Cold Mix Asphalt (Constructors, 2021)

## 2.4 THERMAL PROPERTIES OF ASPHALT PAVEMENT

There are two important thermal properties required for the asphalt pavement.

### 2.4.1 THERMAL CONDUCTIVITY (K) AND DIFUSIVITY OF ASPHALT PAVEMENT

The thermal conductivity of the asphalt layer depends on the properties of its compounds. The typical value of various asphalt mixtures approximately varies from 0.7 W·m/K to 1.7 W·m/K (Khasawneh, 2022). This parameter is limited by the properties of used asphalt bitumen (binder) since the thermal conductivity of bitumen (0.17-0.2 W·m/K) is much lower than the conductivity of aggregate (1.5-2.2 W·m/K). The Thermal diffusivity is a material property that quantifies how quickly heat diffuses through the material in response to a temperature gradient. The thermal diffusivity of asphalt mixtures, like other materials, can vary depending on factors such as the specific composition of the mixture, the type of aggregates and binder used, air void content, and the presence of additives or modifiers. The thermal diffusivity of typical asphalt mixtures used in road construction, such as Hot Mix Asphalt (HMA) or Warm Mix Asphalt (WMA), generally falls within a range of approximately 0.1 to 1.0 $mm^2/s$ (millimeter squared per second) or 10-6 to 10-5 $m^2/s$. This range is consistent with the thermal diffusivity values of other common construction materials. It's important to note that the thermal diffusivity of asphalt mixtures can be affected by the properties of the binder, the aggregate gradation, the presence of additives like polymers or fibers, and the level of compaction achieved during construction. Additionally, factors such as the temperature and air void content in the asphalt mixture can influence its thermal diffusivity.

### 2.4.2 SPECIFIC HEAT CAPACITY OF ASPHALT PAVEMENT

The specific heat capacity of asphalt pavement can vary depending on several factors, including the type of asphalt mix, temperature, and the specific composition of the materials used. The specific heat capacity of typical asphalt materials used in pavement construction is approximately in the range of 0.15 to 0.9 J/g°C (joules per gram per degree Celsius) FHA, (2021). However, these values can vary based on factors such as the type of asphalt binder, aggregate content, and temperature conditions. Asphalt pavement materials are generally considered to have a relatively low specific heat capacity compared to many other materials. This property can impact the way asphalt pavement behaves in response to temperature fluctuations and can affect its thermal performance.

## 3. ASPHALT PAVEMENT TEG BASED ENERGY HARVESTING 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. This can prevent the negative effects of heat on the pavement and as well as providing a sustainable energy source for the powering of road way devices. Some of the Asphalt based TEG systems investigated by researchers include:

Wei Jiang (2017) who developed a road thermoelectric generator system (RTEGS) using vapor chambers and a prototype asphalt pavement (Fig 4). The asphalt mixture slab had dimensions of 0.3 m × 0.3 m, and within it, three aluminium vapor chambers were embedded at a depth of 0.02 m. These vapor chambers were connected to Thermoelectric Generators (TEGs) of the TEG-199 model. The RTEGS generated approximately 0.4V of output voltage in winter and between 0.6V to 0.7V in summer. The power density obtained was 288.89 kWh/m2, 2000 kWh/m2 in the winter and summer respectively.

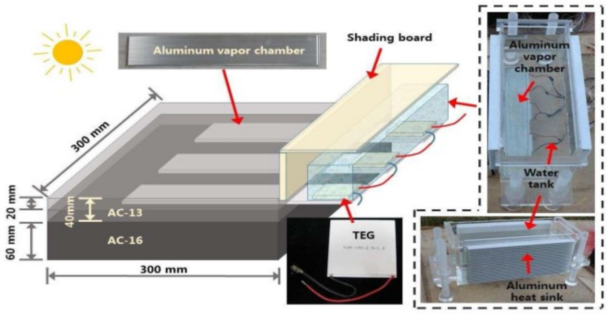

Figure 4: Schematics of RTEGS (Wei Jiang, 2017)

Utpal Datta (2017) developed an energy harvesting system for electric power generation from asphalt pavement. The system includes a z-shaped thermally isolated copper plate as the thermal collector, which is positioned 20 mm below the top pavement surface. The heat collector of 0.072m$^2$. A heat conveyor, 0.15m in length, extends into the soil at a depth of 0.18m (Fig 5). In laboratory experiments, heated water was used to simulate solar radiation with a temperature gradient of 20°C across the thermoelectric module. The results showed that the output voltage ranged from 500mV to 700mV, and the output current ranged from 22mA to 25mA, resulting in an output power ranging from 11mW to 22mW. Field testing was also conducted, with the average output voltage ranging from 480mV to 650mV, the output current ranging from 10mA to 18mA, and the generated output power ranging from 5mW to 16mW.

Seyed (2021) used Finite Element analysis to simulate various prototype designs of an asphalt-based TEG system and tested the most promising prototypes in the laboratory to evaluate their power harvesting capabilities (Table 1). The prototypes includes an L-shaped heat collector/transfer plate with a thickness of 0.15 cm consisting of two segments: A heat receiver with 50 cm length to collect pavement heat and a vertical heat conductor, with length of 18 cm to convey the heat to the lower pavement layers , TEG, and a cooling module with a heat sink made of an aluminum with a size of 18 × 10 × 5 cm was used for absorbing the heat that inadvertently gets transferred between the hot and cold side of the TEGs, phase change material, and insulation box (Fig 6). The results indicated a direct relationship between thermal gradients and power generation, highlighting the importance of the cooling module to maintain efficiency. The optimum harvester design generated an average power output of 29 mWatt or 835 J over 8 hours per day in South Texas.

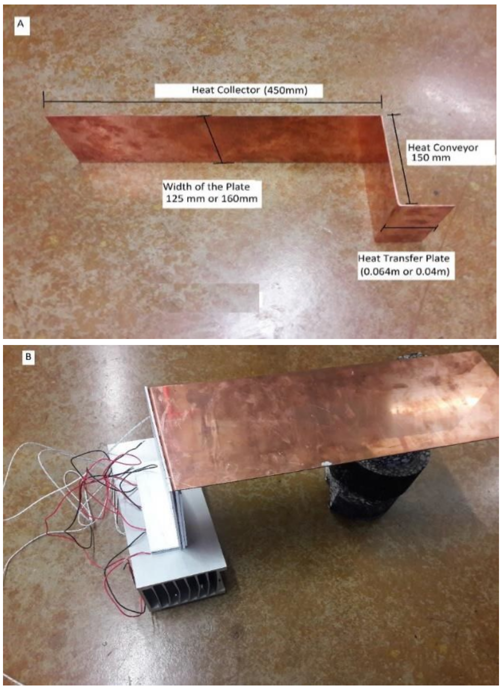

Figure 5: The harvester prototype components include a) Copper plate and b) TEG and heat sinks attached to the copper plate

Table 1: Temperatures for the Different Prototypes investigated by Seyed (2021)

| Designs | High Temp on Collector Plate ($^0$C) | Low Temp on Conveyor Plate ($^0$C) | Temp on Hot Side of TEG ($^0$C) | Temp on Cold Side of TEG ($^0$C) | Temp Gradient on TEG ($^0$C) |
|---|---|---|---|---|---|
| Z-shaped | 46 | 33 | 30 | 19 | 11 |
| 15-L-shaped | 46 | 37 | 32 | 19 | 13 |
| 20-L-shaped | 48 | 41 | 35 | 19 | 16 |
| 25-L-shaped | 48 | 40 | 34 | 19 | 15 |

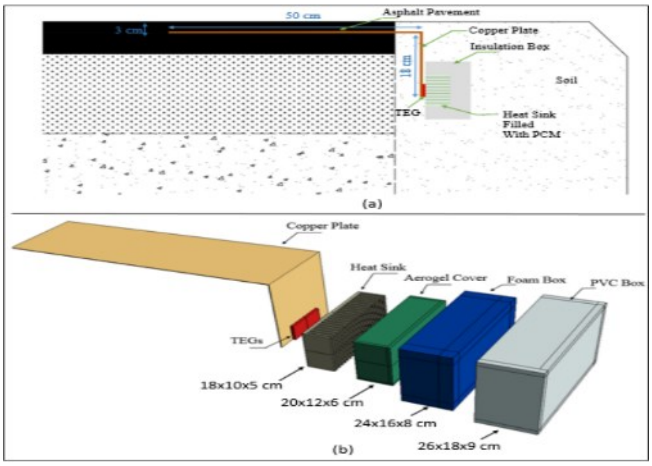

Figure 6: The thermoelectric energy harvesting prototype: (a) schematic of prototype; (b) description of components.

Yuttana Mona, (2021) compared the performance of cement and Ashpalt pavement energy harvesting using TEG Modules (Fig.7). Result showed that asphalt has better solar energy absorption due to its black surface. The TEG modules were placed with the hot surface attached to the pavement's underside which was designed and created in a 150 × 150 mm square box with a height of 50 mm, and the cool surface enclosed by a cooling system. Natural airflow and water-cooling systems were tested, with water cooling providing a larger temperature difference and superior performance. The voltage from the asphalt was higher than that from cement with both cooling methods. The maximum e.m.f. from asphalt was approximately 168.5 mV, about 25.4% higher than that from cement with water cooling (around 134.4 mV). Additionally, this study showed that a pavement thickness of 50 mm efficiently transmitted heat from the upper surface to the lower surface without requiring metal as a heat conductor.

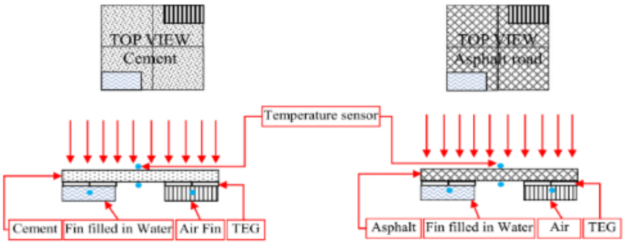

Figure 7: The schematic of cement and asphalt road pavement testing (top) the top view configuration, and (bottom) the cross-section view including the four-point temperature measurement (Yuttana Mona, 2021)

Sharuddin (2021) works on thermal energy harvesting (TEH) from asphalt roads using thermoelectric generators (TEGs) which reveals a promising avenue for sustainable energy extraction. The research focuses on developing an energy harvesting system embedded in road pavements, capitalizing on the ubiquitous waste heat from asphalt surfaces. Experimental investigations, employing aluminium and copper plates under various conditions, demonstrate that copper plates exhibit superior performance, and increasing the number and length of metal plates enhances energy yields. Stacking TEGs in configurations such as 2x2 and 1x4 proves effective in improving output voltage and efficiency. Optimal cooling methods, particularly water tank cooling, are identified to maximize temperature gradients and output voltage. Additionally, the literature delves into the design and analysis of an energy management system, with experiments revealing the superiority of DC1587A in charging supercapacitors due to its maximum power point tracking (MPPT) capability. Overall, the reviewed literature underscores the green, sustainable, and cost-effective nature of TEH from asphalt pavements, highlighting its potential to provide an additional energy supply from excess heat in diverse geographical locations.

Philip Park (2013) study explores thermoelectric energy harvesting as a promising method for converting solar energy into electrical power by utilizing temperature gradients within the pavement depth. However, the low efficiency of energy conversion needs to be addressed for practical applications. The study aims to investigate key factors influencing energy conversion efficiency and determine optimal mechanical and circuit configurations for a customized thermoelectric energy harvesting system designed for pavement applications. The system involves a thermoelectric generator connected to a pair of aluminium heat exchangers. The heat exchangers and TEG are horizontally stacked to avoid transferring mechanical force from traffic loads Fig 8. Factors such as generator type, circuit design, conductive rod shape, and insulation are examined. Three types of cross-sectional shapes for the TEG are tested, and the characteristics of the four different TEGs are summarized in Table 2, where α is the coefficient. Two values of α are provided in Table 2, calculated from specifications and measured in the lab. The results indicate that the generated voltage is approximately proportional to the number of p-n junctions rather than the size of the TEGs. The order of the generated voltage for each TEG is A > B > D > C. The TEG of type B, demonstrating optimal power generation, was employed to assess the impact of θHE Table 3. The flat, rectangular, and rounded heat exchangers, with dimensions illustrated in Figure 8 and corresponding θHE values of 18.6, 9.3, and 4.0 (°K/W) respectively, were examined, the expectation was that lower thermal resistance would facilitate increased heat flow at the heat exchanger, resulting in higher ΔTTEG. The rounded heat exchanger, in combination with type B TEG, achieved a maximum ΔTTEG of 36.5 °K under ΔTHC = 47.8 °K, leading to a power output of 42 mW. This output is 800 times higher than previously reported pavement energy harvesting devices utilizing a TEG.

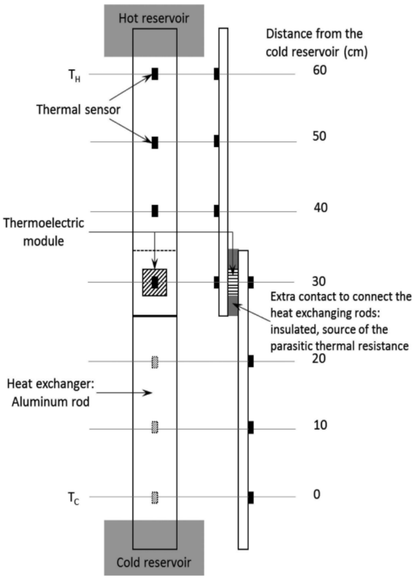

Fig 8. Experimental set-up of the thermoelectric energy harvesting system and Cross-sectional shape and dimension of the heat exchanger (Chen ,2021).

Table 2: Properties of the TEG using in Philip Park (2013)

| | Dimensio (mm) | | | | | | A(V-ΔT coefficient) | |
|---|---|---|---|---|---|---|---|---|
| TEG ID | W | L | Th | Number of p-n junctions | Thermal resistance (K/W) | Electric resistance (Ω) | Calculated | Measured |
| A | 40 | 40 | 4.12 | 127 | 3.45 | 3.57 | 0.0514 | 0.0600 |
| B | 15 | 15 | 5.1 | 31 | 27.50 | 1.60 | 0.0125 | 0.0142 |
| C | 9.5 | 9.5 | 4.7 | 7 | 61.84 | 0.25 | 0.0028 | 0.0031 |
| D | 4.9 | 6.5 | 2.44 | 18 | 115.74 | 2.40 | 0.0073 | 0.0074 |

Table 3: The Effect of TEG types and arrangement on Output parameters (Philip Park, 2013)

| TEG ID | Surface Area of TEG, $A_{TEG}$(mm$^2$) | Parasitic Area, $A_{par}$(mm$^2$) | TEG thickness, *l*(mm) | Parasitic thermal resistance, $\theta_{par}$(k/w) | Thermal resistance at TEG contact, $\theta_{TEG}$(k/w) | Total temp difference ΔT($^0$K) | Tem difference at TEG, $\Delta T_{TEG}$ ($^0$K) | TEG voltage $V_{TEG}$ (V) | Voltage at electrical load $V_L$ (V) | Produced useful power, $P_{out}$ (mW) |
|---|---|---|---|---|---|---|---|---|---|---|
| A | 1600 | 3562.28 | 4.1 | 22.09 | 2.98 | 32.4 | 2.4 | 0.153 | 0.075 | 1.576 |
| B | 225 | 1065.32 | 5.1 | 102.32 | 21.67 | 46.9 | 16.7 | 0.2374 | 0.105 | 6.891 |
| C | 90 | 1200.07 | 4.7 | 80.51 | 34.98 | 38.3 | 14.2 | 0.0436 | 0.0218 | 1.901 |
| D | 32 | 1258.47 | 2.44 | 24.83 | 20.45 | 45.1 | 16.5 | 0.123 | 0.0597 | 1.485 |
| A | 1600 | 3562.28 | 4.1 | 22.09 | 2.98 | 32.4 | 2.4 | 0.153 | 0.075 | 1.576 |
| AA* | 1600 | 3562.28 | 8.2 | 59.71 | 6.19 | 31.7 | 6 | 0.238 | 0.1175 | 1.934 |
| AAAA* | 1600 | 3562.28 | 16.4 | 144.88 | 12.6 | 32 | 9.1 | 0.309 | 0.1548 | 1.678 |

## 5.PERFORMANCE ENHANCEMENT METHODS EMPLOYED IN THE LITERATURE

Various notable works on the investigation of the power that can be produced from TEG systems incorporated into asphalt pavements were described. It will be generally observed that even though the use of TEGs in energy harvesting in the pavements is promising there is the need for the improving of the efficiency of the system for the TEG based energy harvesters to be used in large and real applications. Thus, researchers have focused on developing new strategies for improving the efficiency and these various attempts to improve the efficiency will be discussed in the following sections.

### 5.1 OPTIMIZED THERMOELECTRIC MATERIALS or MODULE:

Choosing high-performance thermoelectric materials with high thermoelectric figure of merit (ZT) values is crucial. Materials with higher ZT values can efficiently convert heat into electricity, leading to improved system efficiency. Zhijia Yang, (2017) presents the experimental synthesis and fabrication procedures of p-type and n-type skutterudite thermoelectric materials, capable of working up to 500°C temperature, with corresponding modules functioning at a maximum of 400°C hot side temperature. The study investigates and discusses the performance loss from materials to modules. Using a validated TEG model, the paper estimates the performance improvement achieved with these modules compared to commercial Bismuth Telluride modules.

Lobunets, (2021) address problems related to the efficiency of thermoelectric generators (TEGs) and the conversion of thermal energy into electricity. The specific issues being tackled include optimizing the power output of thermocouples with a cross-sectional area of 1 cm² and understanding the impact of various factors, such as temperature distribution and boundary conditions, on TEG performance using mathematical model such as the power output of the thermocouple is determined by the thermo-EMF (E) and the internal electrical resistance (R) through the formula Eqn (5a) and The thermo-EMF (E) and internal electrical resistance (R) are defined using the Seebeck coefficient (e(T)) and specific electrical conductivity (q(T)) Eqn (5b), the temperature distribution in the TEG system is modelled using a mathematical approach. The Poisson equation for stationary mode Eqn(5c) bellow. While boundary conditions play a significant role in determining TEG power and efficiency. The author considers three types of boundary conditions (I, II, III). For instance, boundary conditions of type III involve a linear combination of function values and derivatives on the boundary, and they are crucial for describing heat fluxes in convection heat exchange Fig 9. To account for the temperature dependence of thermoelectric material properties, the method of average parameters was applied, where properties (e, r, k) are defined as average integrals in the operating temperature range. The methodology also includes an iterative calculation process and the consideration of load modes to analyse the influence of nonlinearity in boundary conditions on TEG performance. The study also investigates the optimization of carrier concentration tuning under different heat transfer rates, revealing potential improvements in the modified figure of merit (zT') by 1.8-fold.

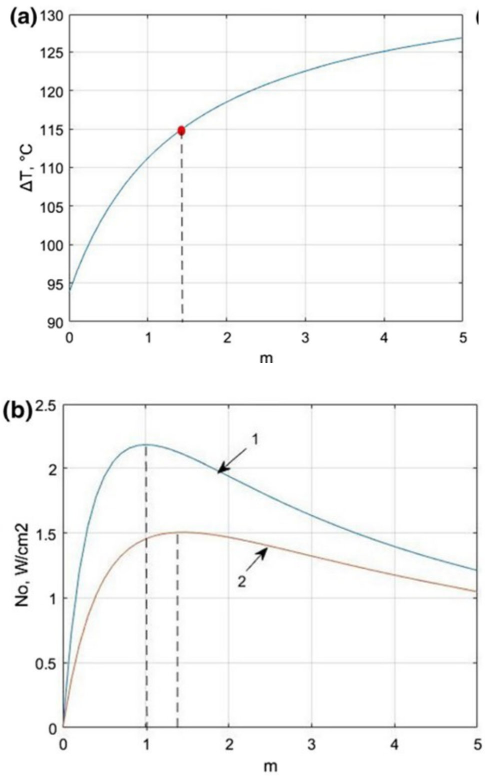

Fig 9. Load characteristics of TEG in boundary conditions of the third type. (a) Dependence of temperature difference on the load factor m=RL/ R. (b) Dependence of power on the load factor.

$$P = \frac{E^2}{Rm}\left(m + \frac{1}{2}\right) \qquad (5a)$$

where $m = \frac{RL}{R}$

$$E = \int_{Tc}^{Th} e(T)dT$$

$$R = \frac{h}{\int_{Th}^{Tc} q(T)dT} \qquad (5b)$$

$$\nabla^2 T + \frac{qv}{k} = 0$$

The use of Variable Area Pins (VAPs) and Nanomaterials have been investigated by Al-Merbati et al. (2013), Bengisu (2020), B.S. Yilbas et al. (2016). These novel materials have better characteristics than the conventional bulk semi-conductors.

The study of Al-Merbati et al. (2013) delves into the thermodynamics and thermal stress analysis of a thermoelectric power generator, focusing on the impact of device geometry on thermal stress, thermal efficiency, and output power Fig10a. The finite element method is employed to predict temperature and stress fields within the thermoelectric device Fig10b. The study highlights the influence of pin geometry on temperature gradients and thermal stress, indicating that a pin with RA=2 results in slightly lower thermal stress, potentially improving the device's life expectancy and thermal efficiency Fig11.

Bengisu (2020) study explores the impact of different thermoelectric leg designs on the performance of thermoelectric devices, aiming to convert waste heat into electricity or manage thermal conditions. Using various leg shapes such as rectangular prisms, hollow prisms, trapezoids, hourglasses, and Y-shapes, numerical modelling was employed to analyse their thermal and electrical performance under constant temperature and heat flux conditions Fig 12. The investigation included two thermoelectric materials, bismuth telluride for low-temperature applications and silicon germanium for high-temperature scenarios. Results revealed that an hourglass-shaped thermoelectric leg, under constant hot side temperature, demonstrated superior thermal and electrical performance, surpassing conventional rectangular shapes. The study emphasizes that leg shape alone is insufficient for optimization, stressing the need to consider varying boundary conditions that reflect different device operating conditions for optimal performance.

In the research of B.S Yilbas et al. (2016), nanowires and nanowalls were created on a silicon wafer using a chemical etching technique. The surfaces of these nanostructures were modified to be hydrophobic by depositing Octadecyltrichlorosilane (OTS) and further enhancing their hydrophobicity with a 1.5-µm-thick layer of n-octadecane coating on the OTS-deposited surface. The hydrophobic properties were evaluated using the sessile water droplet method, and tests including scratch and UV-visible reflectivity were conducted to measure friction coefficient and reflectivity. The modification of surface properties, such as hydrophobicity, can influence heat transfer characteristics and, consequently, the efficiency of thermoelectric devices.

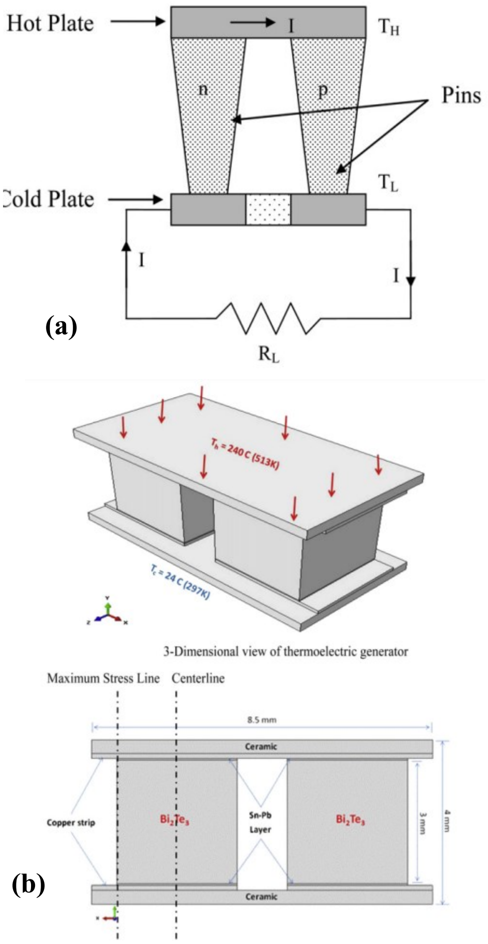

Fig 10. (a) Schematic view of a thermoelectric power generator and pin configurations (b) Three-dimensional view of thermoelectric generator and its dimensions used in the simulations.

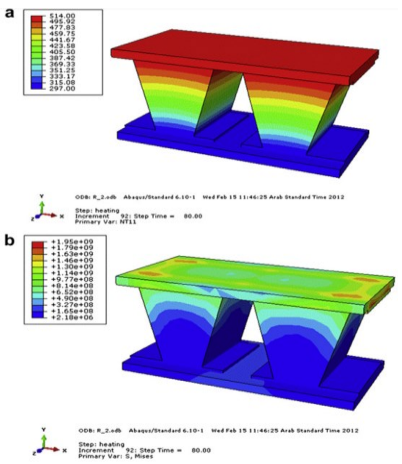

Fig. 11. (a)Three-dimensional temperature distribution in the thermoelectric generator for RA ¼ 2.(b)Three-dimensional thermal stress distribution in the thermoelectric generator for RA ¼ 2.

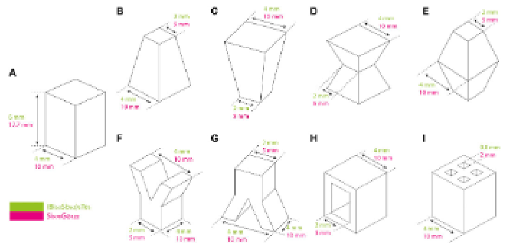

Fig 12. Thermoelectric leg shapes investigated in this study were: (A) rectangular (the conventional leg shape), (B) trapezoid, (C) reverse trapezoid, (D) hourglass, (E) inverse hourglass, (F) Y, (G) reverse Y, (H) hollow rectangular, and (I) multi-hollow rectangular.

Maduabuchi, (2022), conducted an assessment on the use of VAPs enhanced with nanomaterials a using ANSYS 2020 R2 software. Nanomaterial-based asymmetrical VAPs refer to vapor chambers used in thermoelectric generators (TEGs) that incorporate nanomaterials and exhibit an asymmetrical design. These vapor chambers are crucial components in TEG systems, and their asymmetry and use of nanomaterials can significantly enhance the efficiency and performance of the TEG. The asymmetrical design may involve variations in the thickness or composition of the vapor chamber components to optimize heat transfer within the TEG. Nanomaterials, often nanoparticles or nanostructured materials, are integrated into the vapor chambers to improve heat conduction and overall TEG efficiency, making them more effective in converting heat into electricity. The study examined six different leg combinations to thoroughly investigate the impact of leg asymmetry, considering isoflux and convective boundaries. Additionally, the research explored how operating parameters such as load resistance, concentration ratio, and convective film coefficients affect TEG performance parameters, including temperature gradient, power output, and energy efficiencies. The findings were validated by using this model to replicate previous studies and comparing the results. Notably, the study revealed that the proposed nano-enhanced VAP TEG achieved significantly higher power density and efficiency, being 12 times and 6 times greater, respectively, compared to traditional VAP TEGs using conventional materials.

## 5.2 ENHANCED HEAT TRANSFER WITHIN THE ASPHALT PAVEMENT

Ensuring efficient heat transfer from the asphalt pavement to the TEG modules is vital. Improving the thermal interface between the pavement and TEG elements can minimize thermal losses and enhance power generation efficiency. A study of Philip Park (2014) investigate the factors influencing energy conversion efficiency and develop optimal mechanical and circuit configurations for a tailored thermoelectric energy harvesting system for pavements. The studied design includes a thermoelectric generator and thermally conductive rods for heat transfer. The research explores the effects of generator type, circuit design, shape of the conductive rod, and its insulation. The results highlight the importance of controlling heat transfer from the pavement to the thermoelectric generator for effective energy harvesting. Among the tested thermoelectric systems, the best configuration achieved an output of 42 mW, which is about 26 times higher than the default case in the study.

Ali (2022) enhance the efficiency of thermoelectric generator (TEG) devices by using liquid evaporation heat transfer to improve the TEG's performance. They compared the thermoelectric performance under various heat flux conditions and different heat transfer modes, such as free convection, forced convection, free convection with fins, and forced convection with fins. TEG integrated with fins in free and forced modes, and free and forced liquid evaporation convection on the TEG. The findings showed that forced convection improved TEG voltage variation by 116.5%, while the inclusion of fins in free and forced convection modes resulted in voltage variations of 119.8% and 288.4%, respectively. Furthermore, the use of liquid evaporation in free and forced modes improved TEG voltage variation by 73.8% and 435.9%, respectively.

Liu Q. (2012) conducted a study to optimize the mechanical properties of asphalt concrete by adding steel fibers, making it electrically conductive for induction heating. Various tests were performed to assess the impact of the steel wool mixture on different properties. The results showed that the inclusion of steel wool significantly improved the mechanical properties of the asphalt, such as delaying raveling and enhancing self-healing. For the same quantity of steel wool, the asphalt sample exhibited the maximum induction speed and electrical conductivity. This strategy was not implemented for TEGs in Asphalt pavements.

M. T. de Leon, (2010) Introduce a novel approach to enhance the efficiency of thermoelectric generators (TEGs) by employing a lens to concentrate heat onto the TEG's heat source. Initial experiments conducted with discrete components have shown a significant increase of approximately 60mV in the generated voltage when utilizing a magnifying lens. Moreover, simulation outcomes for this proposed TEG configuration indicate a potential efficiency improvement of up to 16%, particularly when the input heat flux is amplified to 500 times that of the sun's heat flux. The study also investigates the impact of varying parameters such as thermoelement length, width, and membrane diameter on the TEG's performance. Finally, the paper outlines future plans to fabricate this innovative device on a silicon-on-insulator (SOI) wafer.

## 5.3 TEG SYSTEM DESIGN AND CONFIGURATION:

Another strategy to increase the efficiency of the TEG system is to optimize the design and configuration of TEG modules to ensure maximum exposure to the temperature gradient across the pavement. Properly arranging the thermoelectric elements can increase energy conversion efficiency.

Aravind (2018) presents a highly efficient prototype of a micro power generator with an integrated micro combustor. The design of the micro-combustor ensures high surface temperature uniformity and flame stability, crucial for thermoelectric power generation. The micro combustor consists of three backward facing steps with a recirculation hole in an aluminium heating medium. Parametric studies are conducted to optimize the operating conditions for maximum power generation. By using liquefied petroleum gas as fuel and incorporating porous media, the system achieves a maximum conversion efficiency of 3.3% at certain conditions, with a possibility of up to 4.03% at higher velocities.

Eman (2018) presents a precise thermal resistance model for a micro-thermoelectric generator (μTEG) fabricated using standard complementary metal-oxide-semiconductor CMOS technology. The model helps determine optimal dimensions for the μTEG, leading to improved output power. The proposed models are validated through three-dimensional simulations and compared to experimental results, demonstrating high accuracy. The study introduces a 1-cm² cross-sectional area μTEG based on a 0.13 μm UMC standard CMOS technology, achieving an output power of 9.25 μW at a temperature difference of 2.34 K. The compact thermal resistance and power models presented are compatible with SPICE-based simulators, facilitating integration with circuit simulations.

In the study of Utpal Datta, (2017) the TEG prototype efficiency was improved by analyzing various thermal harvester models through finite element analysis. An optimum model was selected based on the analysis (Fig. 13) for laboratory testing, followed by field testing under in situ pavement conditions.

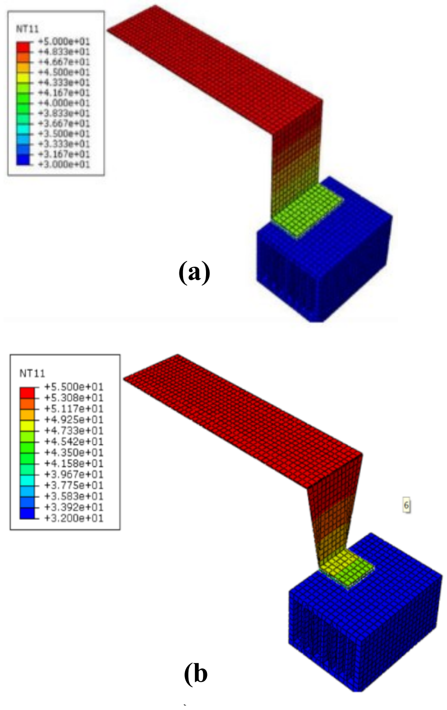

Fig. 13: FE analysis results for a) energy harvesting prototype 1 and b) energy harvesting prototype 2

The performance of thermoelectric generators (TEGs) can be improved either by the adoption of multi-stage or tapered leg configuration. So far, a hybrid device that simultaneously uses both multi-staging and tapered leg geometry to improve its performance has not been conceived. Thus, a thermodynamic modelling and optimization of a two-stage TEG with tapered leg geometries using ANSYS 2020 R2 software was developed. The optimized parameters include the leg height, area, concentrated solar radiation, and external load resistance.

Maduabuchi (2021) compared the performance of different TEG configurations, such as the X-leg TEG and trapezoidal leg TEG, and found that the X-leg TEG improved performance up to a certain leg height threshold. The study also demonstrated that the proposed two-stage TEG with tapered legs (trapezoidal and X-legs) significantly improved the exergetic efficiency compared to a single-stage rectangular leg TEG.

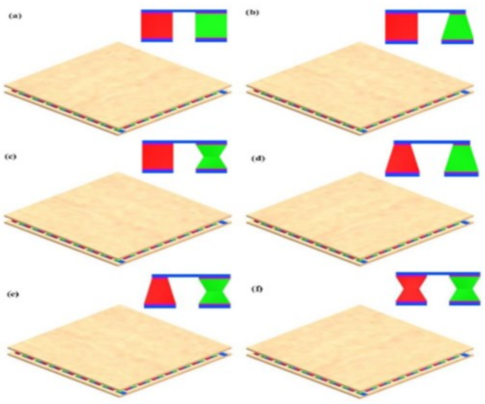

Fig. 14: TEG Module Leg Configurations (Maduabuchi, 2021)

Table 4: Description of Leg Configurations in Fig. 14.

| Cases | Leg geometry |
|---|---|
| A | Rectangular |
| B | Rectangular + trapezoidal |
| C | Rectangular + X |
| D | Trapezoidal |
| E | Trapezoidal + X |
| F | X |

Numerous studies have relied on the simplifying assumption of uniform temperatures for the hot and cold junctions across various TEG models, a practice that does not accurately reflect reality. Notably, when subjected to the same heat source, variable area leg TEGs exhibit distinct temperature profiles in comparison to their counterparts with rectangular area legs. Addressing these research gaps, Madaubuchi (2021) employs ANSYS 2020 R2 software to create a full-scale TEG module equipped with variable area legs, operating under realistic isoflux conditions. The outcomes of this investigation showcase remarkable improvements in the proposed TEG configuration. At an optical concentration ratio of 35 suns, this innovative TEG design demonstrates a substantial 66.15% enhancement in temperature gradient, an impressive 195.07% increase in power density, and a notable 50.18% boost in energy efficiency when compared to the conventional TEG setup. Additionally, the proposed TEG significantly reduces the required solar concentration ratio for achieving peak power density and energy efficiency in comparison to standard TEGs, by 17.39% and 22.22%, respectively. Furthermore, this novel TEG configuration exerts a noticeable influence on electrical load resistance and current, elevating the former while reducing the latter, thereby optimizing overall performance relative to the standard TEG.

Hailong (2022) has introduced a newly developed one-dimensional simulation model aimed at improving thermoelectric generator (TEG) efficiency. Their model was designed with a focus on accuracy and computational efficiency, utilizing numerical solution methods in MATLAB to solve the relevant differential equations. In essence, the research team explored existing TEG models and assessed the feasibility of creating an efficient algorithm for multi-parameter optimization. They employed both analytical and numerical modeling for different components, addressing constant and non-linear physical properties. Furthermore, they developed a one-dimensional TEG model that accounted for variations in material properties based on temperature and spatial factors. The study also examined the impact of irreversible factors, such as heat leakages and contact resistance, on TEG characteristics. Additionally, the researchers devised a hill-climbing algorithm for optimizing the geometry of TEGs and analyzed its advantages. Comparing their results to those of a previously reported three-dimensional model, the authors noted a slight deviation in output power, which validated the accuracy of their one-dimensional model. Furthermore, the maximum output power and heat leakage through the occupied zone exhibited similar magnitudes. The study also reported minimal discrepancies in the thermoelectric module's characteristics and output performance, largely attributed to improved linearity in the output power.

### 5.4 HEAT SINK OPTIMIZATION

Implementing effective cooling mechanisms to maintain a significant temperature difference between the hot and cold sides of the TEG modules is also another strategy for enhancing the performance of the TEG system. Adequate cooling prevents thermal saturation and sustains the energy conversion process. Utpal Datta, (2017) Minimize temperature gradient loss and optimize power generation, by a custom-designed heat sink. The heat sink, filled with a heat-dissipating fluid like water, is placed under the bottom surface of the TEGs to maintain a steady temperature gradient and improve efficiency. To maintain the temperature difference across the TEG Wei Jiang, (2017), designed a water tank similar to that of Utpal Datta (2017) with additional measures, such as shading boards, were utilized to reduce direct sunlight and lower the water temperature in the tank.

Hasebe, (2006) Developed a pavement-cooling system that employed a thermoelectric generator to collect solar heat through a water piping system beneath the pavement. The system effectively cooled the water by utilizing river water, which allowed for sufficient power generation from the temperature difference between the heated transfer medium and the cold water. The laboratory experiments conducted by the authors demonstrated that increasing the flow rate, under a specific electrical resistance corresponding to the electrical load, resulted in improved power efficiency. However, Finite Element Analysis simulations revealed a decrease in power output throughout the day, with a minimum observed when the river water temperature reached its peak. Notably, the study highlighted the relatively low efficiency of the system in powering electrical components, suggesting the need to enhance efficiency through the parallel connection of multiple thermoelectric modules.

Boonyasri (2016) introduces a system designed to reduce the heat from the cold side of a thermoelectric (TE) power generator using evaporative cooling. The application of evaporative cooling has the potential to enhance the conversion efficiency of a TE generator. In this research, two sets of TE generators, each consisting of five TE power modules, were constructed. These modules featured rectangular fin heat sinks attached to both the cold and hot sides. The hot side heat sinks were placed within a hot gas duct. One set of TE generators utilized cooling air from a counter flow evaporative cooling system to cool the cold side, while the other set employed a parallel flow evaporative cooling system. The results revealed that the counter flow pattern outperformed the parallel flow pattern in terms of cooling efficiency. A comparative analysis was conducted between TE generators with and without the evaporative cooling system. The experimental findings demonstrated a noticeable increase in power output when the evaporative cooling system was implemented, leading to a substantial improvement in TE conversion efficiency. Specifically, the evaporative cooling system elevated the power output of the TE generator from 22.9 W (achieved with ambient air flowing through the heat sinks) to 28.6 W at a hot gas temperature of 350°C, marking a significant increase of approximately 24.8%. This study underscores the promising potential of utilizing TE generators with evaporative cooling as an effective approach for waste heat recovery.

Traditional heatsinks used for cooling and lowering the temperature of TEGs are bulky, often being twice the size of the TEG itself. As an alternative approach, Alajingi R. (2022) suggests applying a 120 μm thick acrylic polyurethane-based heat-reflective coating (Thermacool 0.3M) to the cold side of the TEG to achieve the desired temperature reduction. To assess the performance of this proposed system, a TEG (model SP1848-27145) was tested in a controlled temperature environment. Initially, the TEG was tested with a conventional heatsink, and subsequently, with the Thermacool 0.3M coating. A mathematical model was also developed for validation purposes. The study recorded the temperature decrease on the cold side of both the heatsink and the Thermacool 0.3M-coated model over time. It was observed that after 4 minutes of natural convection cooling, the Thermacool 0.3M-coated model achieved a cold side temperature of 34°C, compared to the 39°C cold side temperature of the model with the attached heatsink. This improvement led to significant enhancements in power output (0.18W), efficiency (3.8%), and the figure of merit (0.04) parameters for the Thermacool 0.3M-coated TEG.

Omach, (2021), primary focus was on enhancing the efficiency of a Thermoelectric Generator (TEG) through the utilization of a Maximum Power Point Tracker (MPPT) and a specially designed passive cooling system. The project's methodology involves the simulation of a conventional TEG model using MATLAB, based on the finite volume model, resulting in an initial efficiency of 5.28%. An MPPT circuit is designed in Simulink, accompanied by MATLAB code for maximum power tracking, and integrated with the TEG simulation, resulting in an efficiency of 8.12%. A passive cooling system is then fabricated, based on a thermosiphon design, and integrated with the TEG module. Testing is conducted under various conditions, utilizing a locally available stove as the heat source. Their findings revealed that the integration of the TEG with both MPPT and the cooling system significantly improved its efficiency. The highest achieved efficiency was 8.11%, demonstrating the substantial enhancement in TEG performance achieved through this integration.an empirical model was developed using the performance data collected for a spiral type solar water heating system. This empirical model can be used to predict the annual performance of the solar water heating system using weather data obtained from metrological centres. The model was found to accurately predict the system performance with a maximum weekly error of 11% and a total error based on the 11 weeks of data collected of 1.55 kWh/m$^2$ corresponding to an error of 2.2%. It was also found out that the energy collected for a spiral type solar collector varies linearly with the solar radiation intercepted and the efficiency is independent on the solar radiation intercepted

## 6. CONCLUSION

Researchers have demonstrated that TEGs embedded in asphalt pavement have the potential of cooling asphalt pavements by converting the thermal energy absorbed into useful electrical energy for other road applications. Thus, they have the potential to prevent the negative effects of heat on the pavement and the urban heating Island (UHI) phenomenon. Although Various configurations of TEG prototypes have been tested, most are for prototypes mostly tested in the lab with few that have been field tested. Over the years, researchers have focused on strategies for improving the efficiency of the TEGs for energy harvesting from asphalt pavements. Strategies investigated included:

- Improving the properties of the TEG module or material either by novel fabrication techniques or the use of nano materials, use of VAPs. These strategies proved to improve the performance of the TEGs by up to 12 times.
- Enhancing the heat transfer within the Asphalt Pavement by improving the thermal conductivity of the Pavement by either using liquid evaporation, addition of highly conductive metals into the pavement such as steel fibres and solar radiation concentration onto the asphalt pavement.
- TEG system design and optimization that will improve performance such as considering various thermal harvester configurations, different leg designs such as trapezoidal, X and tapered legs.
- Increasing the temperature difference between the hot and the cold side by employing a well-designed heat sink such as using water to maintain the temperature of the sink, water piping system to provide additional cooling e.t.c

All these performance enhancement methods were found to improve the performance of the TEG system. The reported efficiencies of TEG systems embedded in asphalt pavements are still below 10% and thus there is need to improve the efficiencies and also most of these studies are either numerical or tested in laboratory prototypes.

## 7. RECOMMENDATIONS

In this section recommendations for future research are presented as follows:

- Field Testing of TEG Prototypes:

While laboratory testing has provided valuable insights, the real-world applicability of TEGs in asphalt pavements requires extensive field testing. This would help in understanding the practical challenges and performance under actual environmental conditions.

- Advanced Material Development:

Invest in research for developing new thermoelectric materials with higher efficiency and better thermal conductivity. The use of advanced nanomaterials and novel fabrication techniques should be a priority to achieve significant improvements in TEG performance.

- Optimized Design Configurations:

Further exploration of various TEG module designs, including leg configurations and module arrangements, should be undertaken. Emphasis should be placed on designs that maximize the temperature gradient and enhance heat dissipation.

- Integration with Road Infrastructure:

Develop methods for seamless integration of TEG systems with existing road infrastructure. This includes ensuring the durability and longevity of TEGs within the harsh conditions of road surfaces.

- Renewable Energy Harvesting:

The electrical energy generated by TEGs can be utilized for powering traffic signals, and other road-side applications. This promotes the use of renewable energy sources and reduces dependency on conventional power grids.

- Smart Road Technologies:

TEGs can be integrated into smart road technologies, providing real-time data on pavement temperatures and energy generation. This data can be used for efficient road maintenance and management.

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