Recent Advances in Hybrid Energy Harvesting Technologies Using Roadway Pavements: A Review of the Technical Possibility of Using Piezo-thermoelectrical Combinations

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Abstract

Currently, we are facing an energy transition due to pollution and depletion issues related to fossil energy sources. Among all the efforts to develop alternative green energy sources, there are other energy sources that remain unexplored. Ambient energies present on roadway pavements are one example. Thermal energy from solar radiation and the mechanical vibrations induced by passing vehicles are promising ambient energy sources available from roadway pavements. The aim of this study is to examine the existing energy harvesting systems for these ambient energy sources. This paper also summarizes existing study efforts on hybrid (thermal and mechanical vibration) energy harvesting systems in general. This hybrid system can overcome the limitations of a single source-based system as intermittent and low power generation. Energy harvesting technologies can generate green energy without negative environmental impact during the conversion process. This article solely contains references to studies examining the technological feasibility of a road energy harvesting project. Despite their importance, this bibliographic research did not include attempts to address costs, life cycle analyses, or the impact of the systems on the road structure. The reasons for this omission are due to the difficulty of obtaining this information in the scientific literature for comparison with the suggested systems.

Keywords Thermoelectricity · Piezoelectricity · Energy harvesting · Roadway pavement · Hybrid system

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1 Introduction

Most of our current activities depend on energy. Fossil energy sources are still dominating global energy production. These fossil energy sources are exhaustible and pollute the environment [1, 2]. Furthermore, to address the growth in global energy demand, we must engage in an energy transition [3]. The use of renewable energy sources is thus encouraged to address the problems of depletion and pollution relating to fossil energy sources [4, 5]. Notably, these fossil energy sources are widely used in the field of transportation, and they responsible for 25% of global energy consumption [6]. Most of the current vehicles are still running on fossil energy sources. Roadways are thus a theater for the abusive consumption of fossil fuels from the time of their construction, during their operation and through their end-of-life phase. In this context of the energy transition, apart from the development of electrical and hybrid vehicles [7], another approach is proposed to reduce the impact of fossil energy sources in roadways by turning roadways into an energy farm [8].

For this purpose, studies on energy harvesting from roadway pavement are increasing considerably due to their potential future use [9]. For example, roadways are one of the major civil infrastructures present in our community at present, and roadway pavement was found to cover 29–45% of the urban surface [10]. Roadways are exposed to solar radiation. This heat is then absorbed by the pavement surface and remains unused. Furthermore, this thermal energy can lead to global warming of urban areas, which is known as the heat island effect [11–14]. In addition, each passing vehicle creates mechanical vibrations on the roadway pavement surface, and thanks to the development of technology, it is now possible to convert and harvest these energies (from thermal and mechanical vibration) into electrical energy. In the literature, there are several technologies for harvesting this energy from roadway pavements [15–17], including electromagnetic, piezoelectric, liquid circulation, air circulation, thermoelectric, pyroelectric, and solar panels.

Converting the ambient energy available from road pavements into electricity can supplement current energy sources [18]. Harvesting this roadway energy also allows for the decentralization of the electric power sources and consequently avoids the need for several electrical transportation lines. Another advantage, especially when harvesting thermal energy from roadway pavement, is that it lowers the temperature of the ambient atmosphere. Consequently, the urban heat island effect decreases [19]. Santamouris [20] reviewed approaches to fight the urban heat island effect.

Notably, the use of photovoltaic devices in roadway pavement surfaces has already been studied [21, 22]. Photovoltaic options are viewed as the default solution for harvesting solar energy because they can produce energy in the mW/cm outdoors and μW/cm indoors. Wearing and structure failure are common limitations of these studies. Additionally, the harvesting of mechanical vibration using electromagnetic radiation has also been studied [23] but is associated with difficult maintenance issues. Lastly, the use of piezoelectric and thermoelectric devices to harvest mechanical vibration and thermal energy, respectively, on roadway pavements seems to be more promising [15].

Concerning the measurement of this energy, the main unit is expressed in terms of power, as Watts (W). Theoretically, the energy is the power multiplied by the time, and then the unit of energy is the Watt-Hour (Wh). However, the Watt (W) is commonly adopted in the literature to talk about harvested energy. In addition, in the field of energy harvesting technology, the amount of energy collected is approximately in the milli-Watts (mW) or micro-Watts (μW). Another unit that is widely used in the literature to discuss the power density of a harvesting technology is W cm^{-2}. This unit indicates the output power per unit area and shows how the available surface is exploited to harvest energy. This unit also indicates the technical efficiency of energy harvesting technology. Economical efficiency is evaluated by the Levelized Cost of Energy (LCOE) in dollars per kilowatt hour ($\$.(kWh)^{-1}$).

Gholikhani et al. [15] conducted a review of the existing energy harvesting technologies on roadways. A comparison between the existing energy harvesting technologies on roadways is presented in Table 1. The technology is presented, followed by the principles, the highest power density reported in literature, the advantages and limitations.

Most of the studies about harvesting energy from roadway pavement are focused on only one energy source (thermal energy, mechanical vibration) [15], but a hybrid energy harvesting approach can draw back a single harvester, such as intermittent and inconsistent harvesters [28]. Hybrid energy systems guarantee that electrical energy is available even if there is a lack of one of the ambient energy sources. Furthermore, the output power per unit area can be increased by the use of these hybrid energy harvesters [29]. Thus, this paper will present recent advances in these hybrid energy harvesters in addition to a single harvester using piezoelectric and thermoelectric technologies.

First, the basic principles of how energy can be harvested from piezoelectricity and thermoelectricity are presented. Second, an overview of recent advances in piezoelectric energy harvesting systems is detailed. Additionally, recent advances in thermoelectricity energy harvesting systems are presented. Recent studies on how piezoelectricity and thermoelectricity can be combined to form a hybrid harvester will be reviewed. The aim of this paper is to provide a starting reference for further research on hybrid energy harvesters, which will combine piezoelectricity and thermoelectricity in general and for pavement applications in particular.

Table 1 Comparative table of energy harvesting technologies on roadway [15]

Technology	Principles	Highest power density	Advantages	Limitations
Electromagnetic	Mechanical energy generated by a moving vehicle exerts a pressure on a mechanical system, causing reciprocal motions between a magnet and coil, therefore creating electrical power	647 W/m [24]	High electrical output, no effect on roadway maintenance, not affected by weather conditions	High maintenance requirement due to mechanical components and the influence on the traffic flow, not suitable for all roads
Asphalt solar collector with liquid	The solar radiation are heating pipe embedded in the asphalt layer. A liquid is circulating through the pipe and transport/exchange thermal energy	NA	High energy recovery	Influence on the building and maintenance of pavements, weather-dependent, requires energy to operate, leakage issues
Thermoelectric	Solar radiation heats the thermoelectric generator's hotface, which is embedded in the asphalt pavement. The other face is cooled by a heat sink, and the resulting temperature gradient creates electrical energy.	41 W/m [25]	Provides a broad range of applications and is readily integrated with other technologies	Has a poor efficiency rating and a high unit cost, and is weather sensitive
Piezoelectric	In reaction to applied stress/strain from passing vehicles, piezoelectric materials create electric energy.	5 mW/cm [26]	Is suitable for all types of roads, is insensitive to weather conditions, and can be built in a wide variety of sizes and shapes, it has no harmful influence on the life of the pavement	Costly for the amount of energy produced, and requires a backup package to withstand traffic surges
Photovoltaic panels	PV panels are deployed on the road surface to generate electricity from direct sun radiation	48 W/m [27]	Produces higher energy	High cost, is subject to traffic loads, has a low abrasion resistance, is weather dependant, is reliant on directsun radiation and shadow conditions, and is susceptible to dust and dirt
Asphalt solar collector with air	The solar radiation are heating pipe embedded in the asphalt layer. Air is circulating through the pipe and transport/exchange thermal energy	NA	Deicing, reduction of UHI, and reduction of thermal discomfort, can be utilized in building air conditioning	Weather-dependent, extremely inefficient, and ineffective in cold weather

2 Methodology

The methodology section will develop the approach used in this study for reviewing the literature in the piezoelectric and thermoelectric fields. There are resources and applications available to perform a literature review of a particular area. In this study, the authors used Publish or Perish version 7 (PoP) software for Windows to be as exhaustive as possible for the literature review.

Publish or Perish was developed by Harzing [30] for collecting and analyzing academic literature. PoP uses a variety of data sources, including Google Scholar and Microsoft Academic Search, to obtain raw citations. The users can use PoP to analyze these data according to the following metrics:

- Total number of papers and the total number of citations
- Average citations per paper, citations per author, papers per author, and citations per year
- Hirsch's h-index and related parameters
- Egghe's g-index
- The contemporary h-index
- Three variations of individual h-indices
- The average annual increase in the individual h-index
- The age-weighted citation rate
- An analysis of the number of authors per paper.

In this study, the authors focused on the literature review in the field of piezoelectric, thermoelectric, and hybrid harvesting advances. PoP allows for large research searches with specific parameters, including data sources, authors, years, ISSN, publication name, title word, keywords, and the maximum number of results. To obtain the most significant results in PoP, the authors have used Google Scholar as a data source. Google Scholar is the most commonly used data source for academic literature. Then, two typical words were selected in the "Publication name" parameter for the research review in PoP:

- Piezoelectric
- Thermoelectric

This approach provides a maximum exhaustive list of literature reported for each keyword.

As a result, for the keyword "Piezoelectric", more than 430 academic papers have been found from 1936 to 2020. Piezoelectric-related papers have been cited more than 192,063 times, with an average citation of 2259.56 per year. In addition, the interest in piezoelectric research increased from the 1970s to the 2010s (Fig. 1a). However, a slight decrease in interest in piezoelectrics has been observed during the last decade. This decrease could be caused by the limitation of the electric output by the piezoelectric harvester, which is dependent on the resonance frequency of the system. When the frequency of the vibration source is far from the resonance frequency of the harvesting system, the collected power becomes negligible. In considering this limitation, electromagnetic harvesting systems could be alternative technologies for capturing vibration energy, but their high maintenance requirements limits the growth of this technology.

To determine how many papers are related to roadways, another study was conducted by the authors in Publish or Perish. This time, as a parameter, the word "piezoelectric" is still included in the keyword field, but in addition, the words "roadways AND energy harvesting" are included in the title field. Lastly, 19 academic papers were sorted in accordance with the piezoelectric energy harvesting on roadways.

For the keyword "Thermoelectric", there were more than 410 papers related to this field from 1936 to 2020. It was also noted that thermoelectric papers were cited more than 164,903 times, with an average citation rate of 1940.04 per year. With the delay of a decade compared to piezoelectric papers, the number of thermoelectric papers has also considerably increased from 1990 (Fig. 1b). This interest among scientists in the thermoelectric field during the last three decades is mostly due to its large field of application.

For the combination of piezoelectric and thermoelectric technology as a hybrid energy harvesting system, the two words "Piezoelectric" and "Thermoelectric" have been included in the "Keywords" parameter of PoP. The Boolean logic operator "AND" was added between the two keywords in PoP to list only papers in which the two were studied together. As a result, Fig. 1c shows that these two fields were joined in the literature during recent decades. The interest of researchers in the combination of these two fields is increasing exponentially.

To conclude, the literature on piezoelectrics has reached its peak in the 2000s because of the limitation of the power output of piezoelectric materials. The interest of scientists in thermoelectrics is increasing considerably due to its large field of application. Lastly, the combination of these two technologies has attracted the greatest increase in interest during the last decade. This combination allows for higher power harvesting and could help to address the weaknesses in one another.

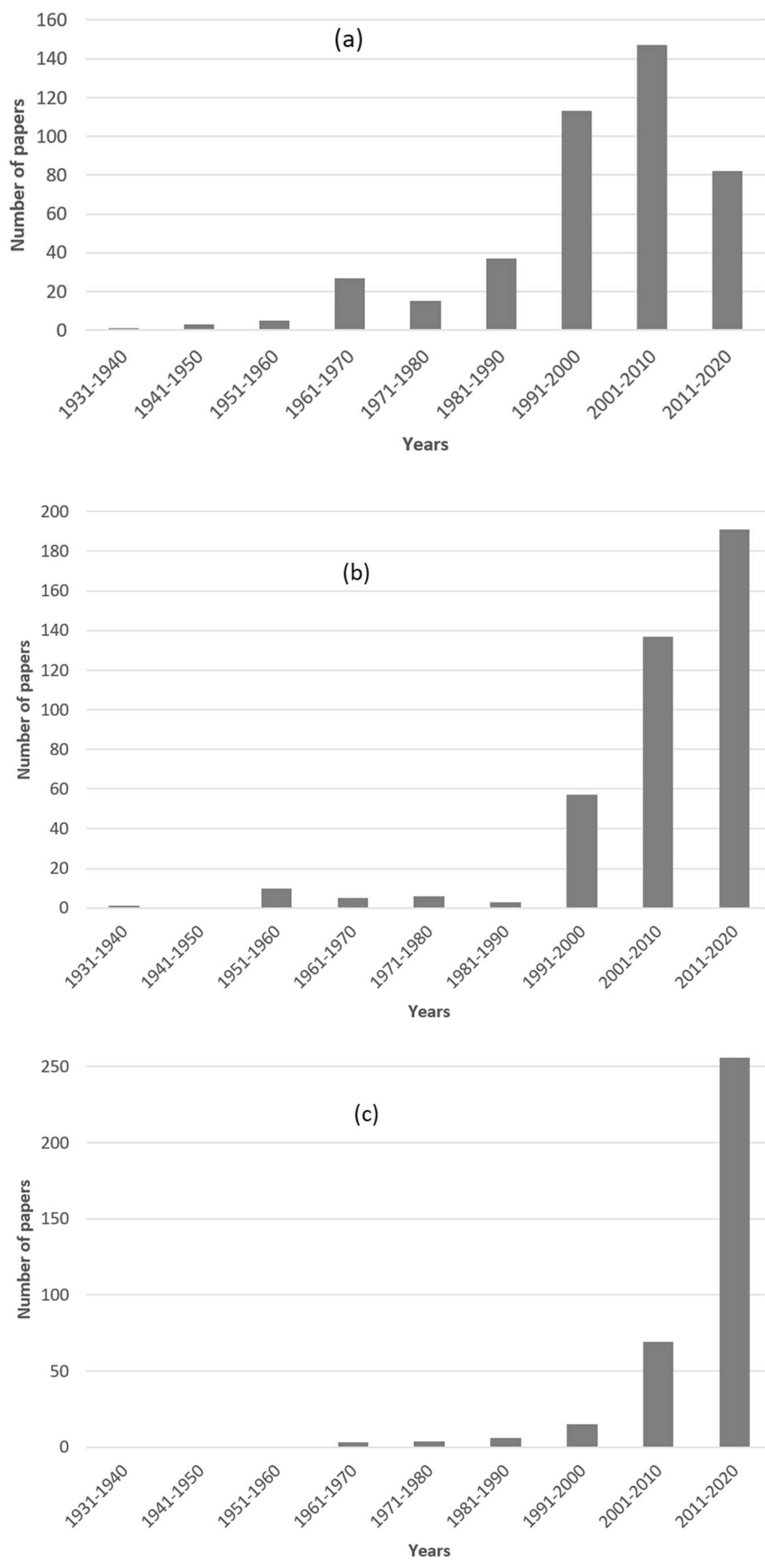


Fig. 1 Number of papers appearance every decade: **a** piezoelectric, **b** thermoelectric, **c** piezoelectric combined to Thermoelectric

3 Basic Principle of Piezoelectricity and Thermoelectricity

3.1 Basic Principles of Piezoelectric Generator

The direct piezoelectric effect in single crystal quartz was discovered by the Curie brothers in 1880. The direct piezoelectric effect appears when a material generates electrical charge/voltage, when that material is under pressure. The word "piezo" is obtained from Greek, which means "pressure". Hence, piezoelectricity is the electricity from pressure [31].

During the First World War, radio waves were used to transmit information. However, these radio waves cannot penetrate seawater, and due to the large loss of shipping resulting from German submarines, a new way to locate submerged vessels had to be found. Thus, generating acoustic waves using piezoelectric crystal quartz was the best solution. That solution has been possible through the method of Langevin [32].

Guo and Lu [33] conducted a review of piezoelectric and thermoelectric harvesting techniques as applied to roads. In their paper, the basic concepts of piezoelectric effects were developed. Thus, piezoelectric materials generate electricity when they are mechanically deformed (Fig. 2). When mechanical compression is applied to crystals, there will be an electric charge [31].

The piezoelectric effect is the transduction of this mechanical deformation into an electrical charge according to these coupling equations:

$$S = s^E T + dE \tag{1}$$

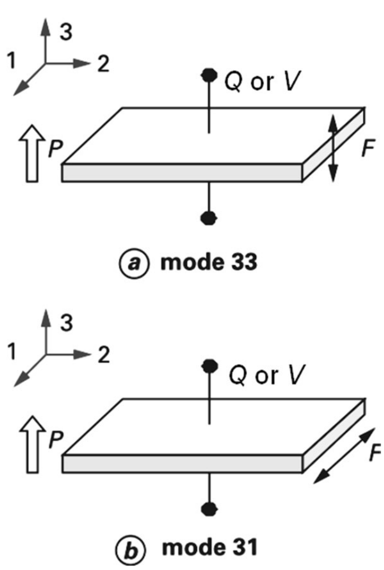


Fig. 2 Piezoelectric effect and deformation mode: **a** mode 33, **b** mode 31

$$D = dT + \varepsilon^T E, \tag{2}$$

where T (Pa) is the stress applied to the material and S (–) is the strain generated by the deformation. E (V/m) and D (C/m^2) represent the electric field and the electric displacement, respectively. s^E (m^2/N) is the elastic compliance for a constant electric field. d (C/N) is the piezoelectric strain constant, which is the charge produced by the application of a force to the material. Lastly, ε^T (F/m)) is the dielectric permittivity for constant stress.

On a roadway, when a vehicle is passing on the surface of the asphalt, this vehicle applies a force to the surface of the asphalt. That force is transmitted to the piezoelectric material embedded in the asphalt layer, and there is a stress T. This stress (T) induces strain (S) and deforms the piezoelectric material. The strain (S) increases when the stress (T) applied to the material increases. Additionally, if the stress (T) applied to the piezoelectric material increases, the electric displacement (D) increases. Thus, a higher electric energy is harvested for a higher deformation of the piezoelectric material.

Two conversion modes are classically used in piezoelectric applications: mode 33, where the deformation is in the same direction as the polarization of the piezoelectric material, and mode 31, where the deformation is perpendicular to the polarization of the piezoelectric material (Fig. 2). The electrical energy at the output of a piezoelectric element is equal to the product of the voltage V and the electrical charge Q. This output energy is dependent on the deformation of the piezoelectric material, and the deformation is dependent on the applied force and the properties of the piezoelectric material. The relationship between deformation and output energy could be expressed in a relationship between the applied force, the dimension and properties of the piezoelectric material and the voltage and electric charge. From the constitutive equations of the piezoelectric element in Eqs. (1) and (2), the expression of the theoretical maximum charge Q when the voltage is zero (short circuit) and the theoretical maximum voltage V when the charge is zero (open circuit) can be established.

For mode 33: $Q = Fd_{33}$ and $V = \frac{Fg_{33}e}{LW}$

For mode 31: $Q = Fd_{31}L/e$ and $V = \frac{Fg_{31}}{W}$

where F (N) is the applied force; L, e and W (m) are the length, thickness and width of the element, respectively; d_{ij} (CN^{-1}) is the piezoelectric charge constant translating the proportionality between the electrical induction and the stress; and g_{ij} (m$^2C^{-1}$) is the piezoelectric constant of voltage translating the proportionality between the electric field and the stress.

To identify the use of a piezoelectric material, Uchino [31] listed five important figures of merit:

- The piezoelectric strain constant d, which is the magnitude of the induced strain x divided by an external electric field E

$$d = x/E \tag{3}$$

- The piezoelectric voltage constant g, which is the induced electric field E divided by an external stress X

$$g = E/X \tag{4}$$

- The electromechanical coupling factor k, which is the conversion rate between electrical energy and mechanical energy

$$k = \sqrt{\text{Stored\_mechanical\_energy/Input\_electrical\_energy}} \tag{5}$$

or

$$k = \sqrt{\text{Stored\_electrical\_energy/Input\_mechanical\_energy}}. \tag{6}$$

- The mechanical quality factor Q_m

$$Q_m = \omega_0/2\Delta\omega, \tag{7}$$

where ω_0 is the resonance frequency, $2\Delta\omega$ is the full width at $Y_m/\sqrt{2}$, and Y_m is the motional admittance.
- The acoustic impedance Z, which assesses the acoustic energy transfer

$$Z = \sqrt{\rho/c} \tag{8}$$

where ρ represents the density of the material and c represents the elastic stiffness of that material.

3.2 Basic Principles of Thermoelectric Generator

The thermoelectric phenomenon was discovered and understood macroscopically from 1821 to 1851 [34]. During that period, the applicability of thermoelectrics was recognized in the field of thermometry, power generation, and refrigeration. From the late 1930s, thermoelectricity was understood on a microscopic scale. This step allowed for the development of present-day materials.

Thermoelectric materials turn thermic energy into electrical energy. This phenomenon is made possible by the Seebeck effect. This effect takes advantage of the characteristics of two different metals or semiconductors to generate electricity [35]. When these two metals are exposed to a difference in temperature, a voltage appears between them. In their study, Guo and Lu [33] also described the basic concepts of the thermoelectric effect (TE) for harvesting energy, as shown in Fig. 3. The primary equation of a thermoelectric generator is:

$$V = \alpha(T_\mathrm{h} - T_\mathrm{c}), \tag{9}$$

where V (V) represents the voltage between two dissimilar metals or semiconductors; α (V/K) represents the Seebeck coefficient and $T_\mathrm{h} - T_\mathrm{c}$ (K) represents the temperature difference between the hot and cold sides.

The amount of energy harvested from the thermoelectric generator is directly dependent on the temperature gradient between the two faces of the generator. On a roadway, solar radiation heats the surface of the asphalt layer. The

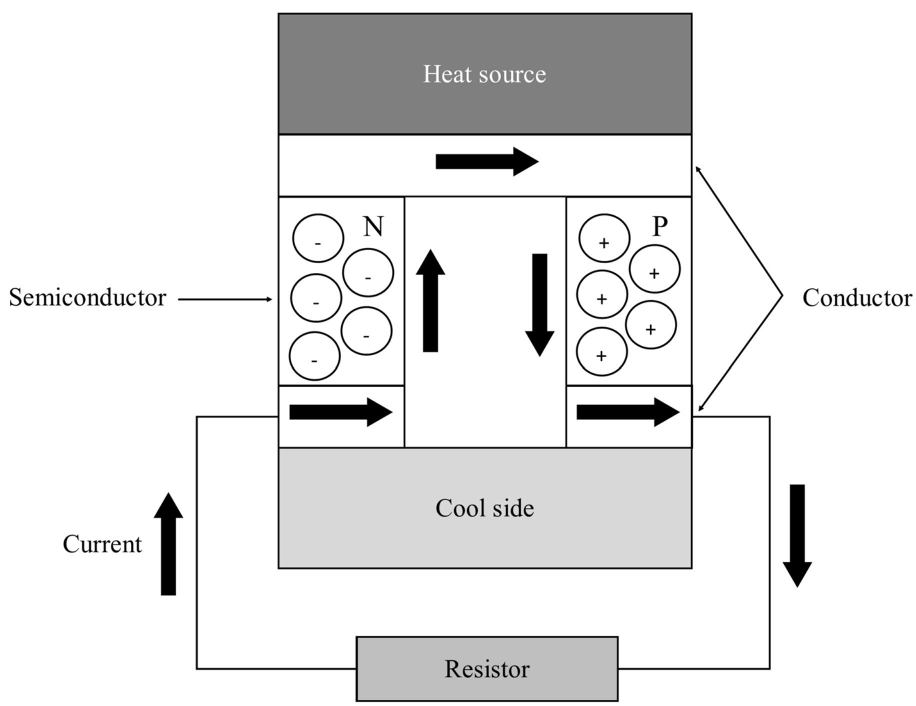


Fig. 3 Thermoelectric effect [33]

thermoelectric generator is embedded in the asphalt layer. The performance of the thermoelectric harvester is then affected by the thermal conductivity of the asphalt layer. If the asphalt layer has good thermal conductivity, there will be a small temperature difference between the surface of the asphalt and the hot face of the thermoelectric generator. Thus, a higher energy could be harvested.

The performance of thermoelectric materials is identified first by the power factor (PF) [36] according to the relation:

$$PF = \alpha^2.\sigma, \tag{10}$$

where α is the Seebeck coefficient and σ is the electrical conductivity.

Then, the usefulness of a thermoelectric material can be determined by the device's efficiency. Therefore, the maximum efficiency of thermoelectric material is established by the figure of merit [37]. When this factor is high, the material is more efficient. This figure of merit depends on the temperature, and the material can present a better figure of merit according to a particular selection of temperature [38]. This figure of merit is dimensionless and is represented by the following relation:

$$ZT = \alpha^2.\sigma.T/k, \tag{11}$$

where α, σ, T, and k represent the Seebeck coefficient, electrical conductivity, temperature, and thermal conductivity, respectively.

3.3 Principles of Road Pavement for Thermal and Piezoelectrical Generation

A road pavement consists of a number of layers of mostly granular (and sometimes stabilized) materials, with a bituminous surfacing (seal to asphalt layer). These layers function as a unit, providing support to vehicles traveling on road pavement. When a vehicle travels on the pavement surface, the surface deflects. The magnitude of this deflection is dependent on the mass of the vehicles, the speed of the vehicle and the properties of the pavement materials. The interaction of the vehicle tires with the pavement surfacing therefore causes movement that is used in the piezoelectric principle of generation. From a thermal viewpoint, the bituminous surfacing is typically dark to black in color, absorbing ultraviolet and infrared radiation during the day. This absorbance causes an increase in the temperature of the road surfacing, with the temperature migrating into the bottom part of the bituminous surfacing throughout the day. When the temperature differential between the top and bottom of the bituminous road surfacing is at a maximum (i.e., early morning (top hot and bottom cold) and evening (top cold and bottom still hot)), it allows for thermoelectrical generation due to the temperature difference, as discussed elsewhere in this paper.

4 Single Source Harvesting Technologies on Road

4.1 Review on Piezoelectric Energy Harvesting

The harvesting of energy from mechanical vibrations in asphalt pavement has attracted increasing interest among researchers. Piezoelectricity, which is based on Curie's principle, transforms mechanical stress into electricity. However, there is a close relationship between the harvested energy and the asphalt pavement [39]. Other applications of the use of piezoelectricity were studied in the literature. For instance, to collect energy from footsteps [40, 41] or for automobile applications [42–44].

This increasing interest among researchers in harvesting mechanical energy from roadway pavements with piezoelectric transducers has occurred because these transducers have a higher power density according to a comparison study by Papagiannakisas et al. [45]. Their work has compared the power density and voltage of various energy harvesting technologies: solar cells, fuel cells, electromagnetic, thermoelectric, piezoelectric, etc. Lastly, piezoelectric technologies have displayed the most interesting results according to their power density and voltage.

4.1.1 Designing and Modeling

Studies in the literature propose several approaches to harvest energy from pavement vibration. However, four types of PZTs have been commonly used in research: ZT cymbals, PZT piles, PZT stacks, and PZT cantilevers.

Some studies consist of the modeling of the energy harvester. Electromechanical models are mostly used for this purpose. Khalili et al. [46] suggested a pavement piezoelectric energy harvester. Their harvester includes a stack of piezoelectric elements. These elements are then connected in parallel. An electromechanical model of that piezoelectric harvester has then been proposed for low frequencies varying from 2.5 to 62 Hz (Fig. 4). This electromechanical model of the piezoelectric harvester is commonly used in the literature [47].

Guo and Lu [50] also proposed an energy harvesting pavement system. The concept of their study was to use conductive asphalt and piezoelectric materials. The primary objective of their study is to propose a new harvesting system, and a three-degree-of-freedom electromechanical model was used to optimize the system. Figure 5 is the representation of that three-degree-of-freedom model. The upper asphalt concrete, the piezoelectric elements, and the lower asphalt concrete are the three compressible and deformable elements of that three-degree-of-freedom model. The force from the passing vehicle induces a first deformation to the upper asphalt layer. Then, it transmits the force

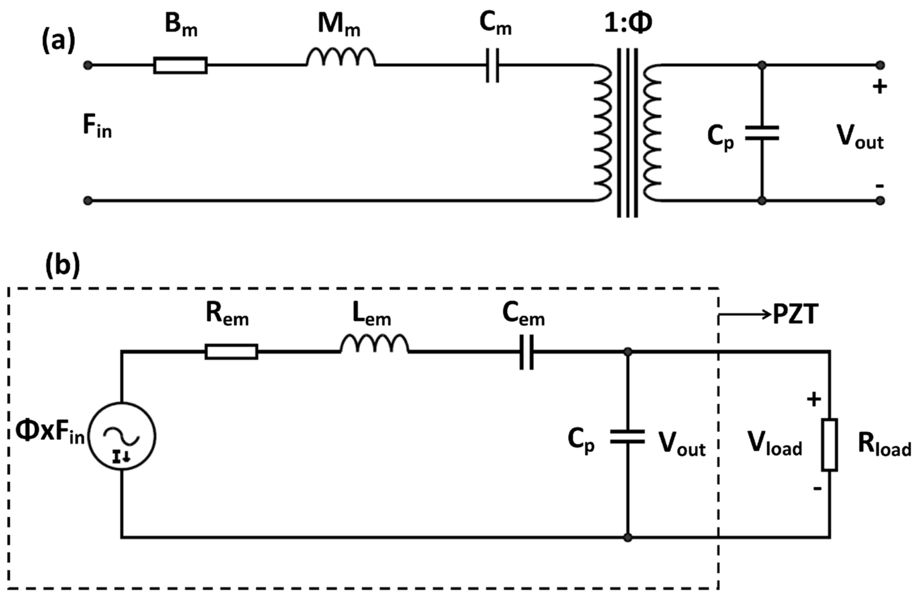


Fig. 4 Mechanical model (**a**) and equivalent electrical model (**b**) of a piezoelectric material [46, 48, 49]

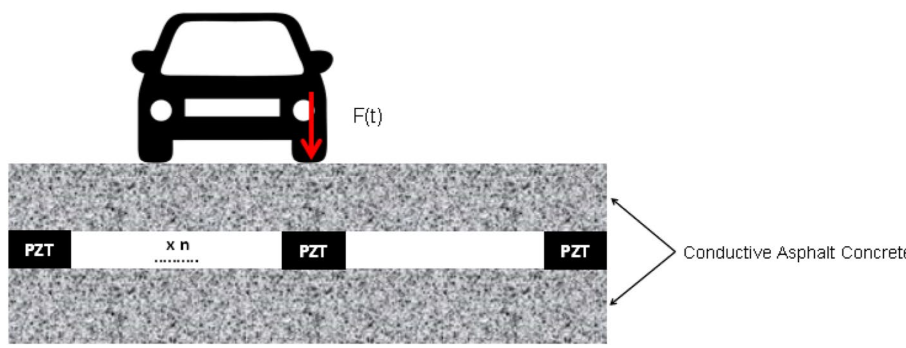


Fig. 5 Three-degree-of-freedom model of the harvester prototype [50]

to the piezoelectric element, which transmits to the lower asphalt layer. The harvested energy was obtained through this electromechanical model and verified by experimentation. Finally, their research led to a maximum electrical power of 300 mW.

Some studies have focused on the structure of the piezoelectric element to maximize the harvested energy. Wang et al. [51] studied the use of multiple layers of cantilever piezoelectric transducers. The configuration of the cantilever was in parallel and was disposed of under the road pavement. Wang et al. [52] also proposed stacking multiple piezoelectric harvesters. However, their study focused on typical structure combinations using PZT-5H transducers. These transducers were stacked.

Some studies are based on a numerical approach using the finite elements method (FEM). Papagiannakis et al. [45] developed an energy harvesting technique. In their work, piezoelectric elements are included in the road pavement block. Their research contained a design and testing approach to the system under a controlled stress environment in a laboratory. Furthermore, the numerical modeling of the stress partition through the piezoelectric element has been conducted by FEM.

Guo and Lu [53] proposed a numerical analysis of a piezoelectric harvester. The principle of their work is to include dissimilar forms of piezoelectric modules inside the piezoelectric layer. These forms can be a piezocylinder, piezocurved roof, and piezo-ball. Guo and Lu also developed FEM under laboratory conditions. Then, experimentation was performed to confirm their study. Their research showed that a thin piezoelectric bed combined with piezo-balls can produce a voltage of 85 V, while a thick piezoelectric bed combined with piezo-cylinders can produce 50 V.

There are many studies on piezoelectric harvesting systems. According to each study, the depth of the PZT sensor may vary from one study to another. Roshani et al. [54] proposed embedding a PZT sensor beyond a depth of 50 mm to allow for the maintenance and repair of the pavement surface. Under these conditions, 90% of the stress on the surface is transmitted to the PZT sensor, and pavement rehabilitation is still possible.

The primary technology used to collect the electricity generated from across the pavement stretch is supercapacitors. The electrical outputs of different groups of sensors are connected to the supercapacitors. The harvested energy could be stocked and used thereafter.

One of the primary outputs of a harvesting system is the power density, which is the harvested energy per area. The number of sensors per lane km of road thus depends directly on the power density of the proposed system. In a simulation, Guo and Lu [33] proposed using ten PZTs for a 1-m roadway lane without stacking piezoelectric components. This disposition conducts up to 10000 PZTs for each lane km.

The power generated from a piezoelectric harvester depends on the vibration frequency, the stress applied to the surface and the electromechanical characteristics of the piezoelectric element. Among these three parameters, the speed of the vehicle influences the vibration frequency of the road, as demonstrated by Song et al. [55]. To collect the maximum amount of energy from a piezoelectric harvester, the frequency of the vibration source (passing vehicle) has to match the natural frequency of the harvesting system. Thus, a resonance phenomenon appears, and the maximum amplitude of power is harvested. The vibration source frequency correlates with the speed of passing vehicles.

The presence of moisture could impact the PZT sensor by oxidation and could affect the performance of the harvesting system. For that reason, moisture should be avoided by adding a moisture evacuation system to the prototype. If the moisture is from the pavement structure, an evacuation pipe should be installed in the asphalt layer. During low energy production (such as when starting a car), the combination of the piezoelectric system with an electromagnetic system may be an alternative solution.

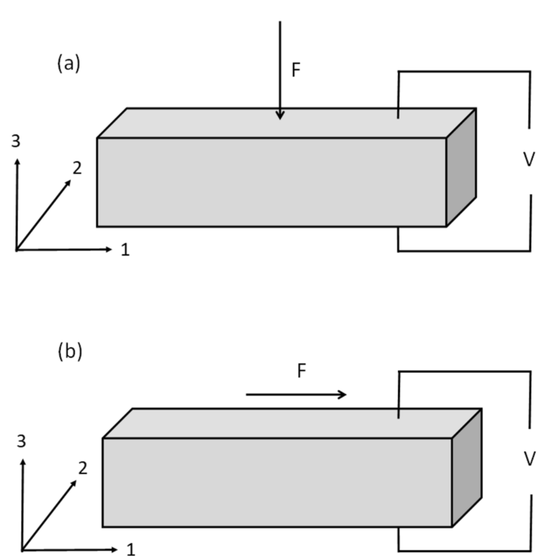


Fig. 6 Piezoelectric modes: 33-mode (**a**) and 31-mode (**b**) [56]

To harvest energy from mechanical vibration, two modes are commonly used: 33-mode and 31-mode. In the 33-mode, the stress and the generated voltage are set in a similar direction, while in the 31-mode, the stress and the generated voltage are perpendicular (Fig. 6). The energy harvesting techniques from pavement vibration commonly use the 33-mode according to the direction of the vibration generated by passing vehicles [56].

4.1.2 Experimentation and Validation

An energy harvester from the pavement is applied to different road conditions. Additionally, the road compositions are distinct, and the equivalent stress and strain effects are also distinct. Consequently, the generated current is different under these dissimilar conditions.

Experimentation on each proposed energy harvester is therefore necessary, followed by validation. This section will report on some experimentation and validation research that was conducted recently. Khalili et al. [46] simulated an equivalent electric circuit. To run a simulation and compare the results with the experimentation, the electrical model circuit was designed in a simulation environment using MATLAB/Simulink®. A laboratory measurement was then conducted. As a result, the maximum voltage generated by their prototype may vary from 95 to 1190 V with an external charge of 500 kΩ when the frequency of loads is 66 Hz. Furthermore, the root-mean-square power generated by their work ranged from 9 to 1400 mW. The work of Khalili et al. concerns the electromechanical characterization of a piezoelectric energy harvester. Laboratory testing and simulation were conducted for that purpose. During the characterization, different ranges of parameters were used. The dynamic loads ranged from 1.1 to 11 kN, and the loading frequencies ranged from 2.5 to 62 Hz. However, in roadway applications, the road vibration frequency is lower (ranging from 10 to 22 Hz). A relationship between the road vibration and the road frequency utilization was established experimentally by Song et al. [55].

Wang et al. [51] simulated the stress state of the energy harvester. Thus, their study required the use of an oscilloscope, a force transmission component, and a clamping fixture. The characteristics of the composition were then studied under specific road situations. Their research also addresses the optimal structural parameters to avoid the ignorance of durability in the study. Lastly, a generated voltage of 5.2 V and a generated power of 3.14 mW by their energy harvester were found under a 5 Hz vibration. The power density corresponds to 0.0063 mW/mm^3.

Wang et al. [52] also conducted some tests for another embedded piezoelectric harvester. Different compositions of pavement components, distinct operating temperatures, and the work durability of power pavement have thus been tested during their study. Wang et al. made the following statements: “the hidden depth of the piezoelectric harvester and the electrical output are inversely proportional. Also, the generated voltage and power increase linearly with the load. Finally, the generated voltage and power increase when the pavement is getting hotter.”

Guo and Lu [33] also performed a laboratory test on their piezoelectric harvester to validate their electromechanical model. For this purpose, an material testing systems (MTS) was used to imitate the appropriate frequency and magnitude of traffic loads. Their laboratory tests showed that the generated voltage may vary from 4 5 to 7.6 V, corresponding to a load amplitude varying from 88 to 133 N and a frequency of 1 Hz. Thus, the accuracy of the proposed electromechanical model was validated by laboratory tests.

In the case in which a sensor is damaged during operation, all the sensors mounted in series with that damaged sensor are out of order. For that reason, the sensor mounting should be separated into several groups. For example, a group of 10 sensors is mounted in series, and that group should be mounted in parallel with the other 10-sensor group. In that configuration, a damaged sensor will not affect the entire harvesting system. However, in the case of embedded PZT sensors, they cannot be replaced until road rehabilitation occurs.

Moure et al. [57] built and tested a variety of 29 mm diameter piezoelectric cymbals to enhance mechanical to electrical energy conversion. The top performers are placed straight into asphalt to be tested as vibration energy harvesters on roads. The cymbals and their asphalt incorporation are defined. Each cymbal can recover 16 µW for each wheel pass. Integrated cymbals address energy changes on high vehicle density highways like peri-urban motorways. A 100-m road (30,000 cymbals) could generate 40–50 MWh/m^2 per year, or 65 MWh total. Their work proposed a harvesting system which the cost of energy per kWh is under 2 euros.

Gholikhani at al. [15] conducted a critical review of piezoelectric technologies applied in the roadway. Their work showed that there are very different outputs in the existing piezoelectric harvester studies. In term of generated voltage, there are distinct categories followed by the reference of examples:

- generated voltage superior to 100 V [58–63],
- generated voltage from 50 to 100 V [53, 64],
- generated voltage inferior to 50 V [65],

Additionally, there are also different categories according to the maximum generated power:

- generated power greater than 100 mW [50, 58, 66–70]
- generated power from 50 to 100 mW [71–73]
- generated power less than 50 mW [55, 65, 74–86]

The existing designs of piezoelectric harvesting systems are embedded into the layer of asphalt to harvest the mechanical energy from passing vehicles. The more mechanical energy is transmitted to the piezoelectric system, the higher the electric energy generated. The main inquiry is the damage caused by traffic on the harvesting system. The objective of a harvesting system is to collect and transduce the greatest amount of energy. For that purpose, installing the system away from the wheel path to avoid damage from passing vehicles is not the best option. This configuration will considerably limit the amount of harvested energy and derive from the main objective. An adequate solution could embed the harvesting system into an optimum depth so the energy harvested is at an acceptable value without considerable loss and is not subject to damage from the passing vehicle. Roshani et al. [54] proposed to embed the harvesting system at 50 mm, so 90% of the stress on the surface are transmitted to the piezoelectric transducer and this depth also allows the maintenance of the pavement surface. Such configuration could address the issue of low energy and damage related problems.

To summarize, harvesting energy from the mechanical vibration of pavement is attracting increasing interest. However, it is more interesting to apply this harvester in traffic with higher vehicle speeds. Effectively, most existing studies have generated a power density of less than 50 mW. Higher vehicle speeds lead to greater generated voltage and power. Thus, piezoelectric harvesters are more effective for highways because highways have fewer speed constraints than cities. However, deeper studies regarding the impact of embedding a harvesting system into the pavement structure are needed. Deeper cost studies are also missing in the current literature to evaluate the economic viability of these technologies. To enhance the electrical outputs of a piezoelectric harvester, future research should focus on the improvement of piezoelectrical materials, on the disposition of the harvesting system to maximize the vibration speed, and on the electronic systems used to maximize outputs.

4.2 Review on Thermoelectric Energy Harvesting

The principle underlying thermoelectric materials is to convert thermic energy into electrical energy through the Seebeck effect. Roadway pavement is exposed to sunlight throughout the day, and the temperature of the pavement is often greater than the ambient temperature due to its dark color. This exposure of the pavement to heat is attracting research interest toward harvesting this unused heat and converting it into electricity. Thus, this section will describe recent studies about thermoelectric energy harvesting.

4.2.1 Designing and Modeling

The temperature difference between pavement layers is harvested to produce electricity using thermoelectric generators. The Seebeck effect appears when an electrical voltage is generated between the hot and cold junctions of a thermoelectric harvester. Some studies on pavement energy harvesting use a pipe system that is included in the pavement. In this case, a temperature difference is exploited among hot and cold fluid circulating inside the pipe system [87–92]. However, the primary issue involved in using these systems is that pipes can be damaged under high or intensive traffic loads. In addition, these systems are difficult to access for maintenance in the case of leakage [33]. The typical fluid type used in pipe systems is water. Water is affordable and is not a danger to the environment. In other studies, antifreeze liquid is used especially for deicing [93]. The dimensions of the pipe may vary from one study to another. Wu et al. [94] proposed a pipe system with a pipe diameter of 15 mm. The space between the two pipes was 100 mm, and the pipe was organized in a serpentine form at a 75 mm depth. Xu et al. [47] also arranged the pipe in serpentine. However, the diameter of the pipe was 20 mm, and the spacing between two pipes was approximately 120 mm or 160 mm. These pipes were embedded at 90 mm or 160 mm depths.

Figure 7 describes the primary principle for using a pipe system to harvest thermal energy from roadways.

Thus, the use of thermoelectrical modules directly in pavement layers represents more ways to avoid these issues. Jiang et al. [96] developed a set of "Road Thermoelectric Generator System" (RTEGS). In their study, three key principles were included in the design of their harvester [96]:

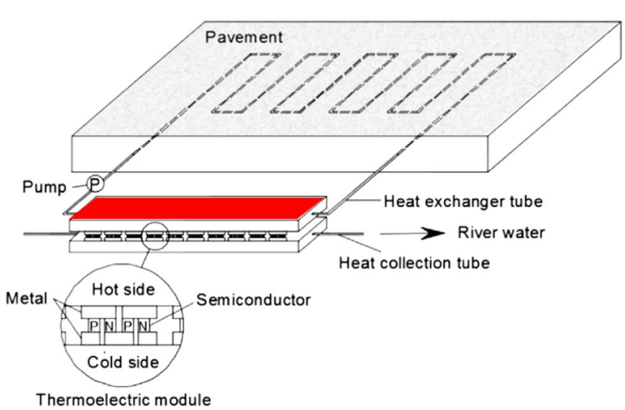


Fig. 7 Diagram of a pipe system [95]

- to efficiently accumulate thermal energy from the asphalt structure;
- to maximize the use of the temperature gap among the road and ambient air;
- to reduce the consequence of installing RTEGS on the asphalt structure.

For this purpose, Jiang et al. [96] placed vapor chambers at 20–30 mm depths through the pavement to conduct the heat energy of the road to the TEG. These vapor chambers are perpendicular to the roadway and lead the heat to the roadside where TEGs are bonded. This part is the hot part of the RTEGS, and the cold part is the one connected to the water tank. The TEGs are then assembled in series to produce electricity from the temperature gap among the hot and cold parts.

Dutta et al. [95] also designed a thermoelectric energy harvester. In their study, a Z-shaped thermally isolated copper plate was used to carry the thermic energy from the pavement surface to the TEG. The design can be cut into three distinct parts. First, a heat collector was embedded 20 mm under the pavement surface. Second, a heat conveyor was insulated by a 2.5 mm thick layer of polyvinyl chloride (PVC) to minimize losses during heat transportation. Lastly, a heat transfer plate was used to transfer the thermic energy to the top of the TEG. The bottom of this TEG was connected to a heat sink to maximize the temperature difference and enhance the harvested energy (Fig. 8). The depth of the heat sink ensures that the influence of the ambient air temperature is negligible for the cold face of the thermoelectric generator. Then, if the heat sink is placed at a low depth, the ambient air could impact the cold face of the thermoelectric generator. If the heat sink is embedded deeper, better isolation is established. When the heat sink is isolated, the temperature gradient of the thermoelectric generator increases, so the energy is collected. Thus, the depth of the heat sink affects the performance of the harvesting system because it affects the performance of the thermoelectric generator.

Tahimi et al. [97] also proposed a new configuration for the harvesting system. Their study presents some similarities compared to the research of Dutta et al. [95]. The proposed system is composed of a heat collector combined with a thermal electric generator and a coolant module. The difference compared to Dutta's system is that the heat sink of Dutta's system is replaced by a coolant module. This coolant module is formed by phase change materials, aerogel covers, foam boxes, and PVC boxes. Additionally, for the design of the prototype proposed by Tahimi et al. [97], the copper plate is L-shaped.

The prototype proposed by Tahami et al. [97] was designed to be directly embedded into asphalt pavements. In their study, finite element simulations were performed to verify the characteristics of the harvesting

Fig. 8 Thermoelectric harvester prototype [95]

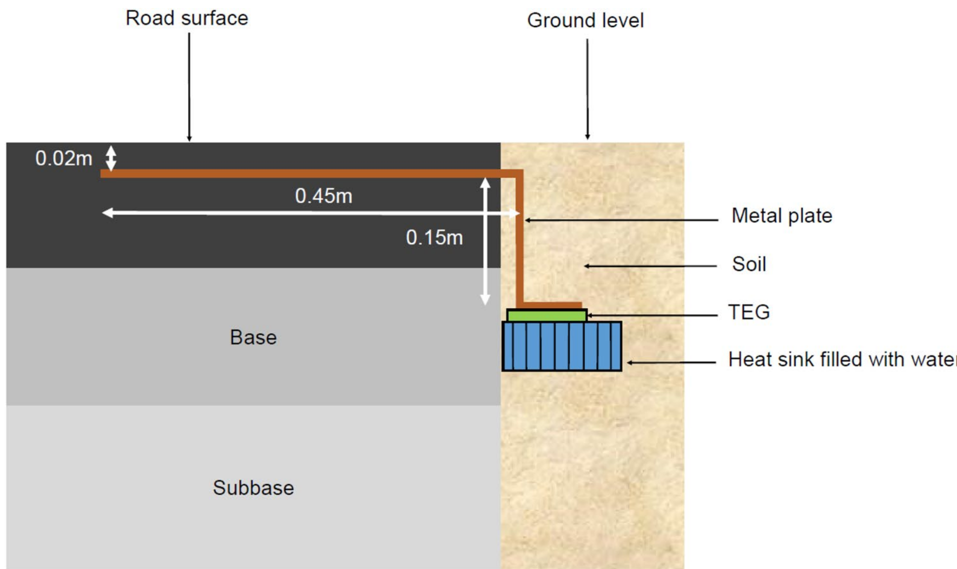
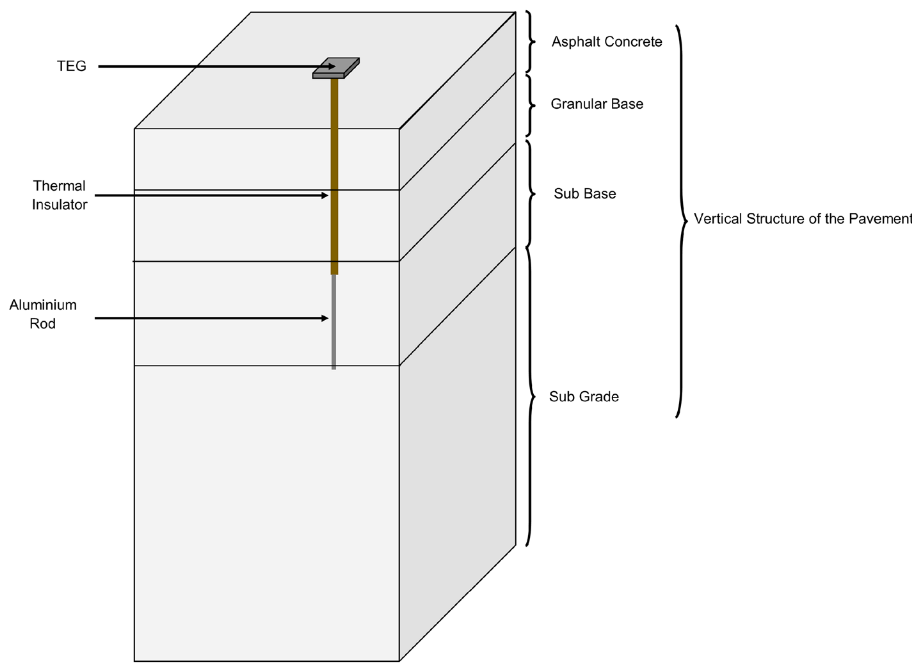


Fig. 9 Components of the energy harvest system and vertical structure of the pavement [98]



system components. These simulations also allow for the optimal design of the prototype to be determined. The L-shaped plate with a 200 mm width was found to present the highest temperature gradient and consequently presents a higher amount of harvested energy. Additionally, their study showed that the performance of the system is enhanced if we incorporate a phase-changing heat sink in the coolant module.

Wu and Yu [98] conducted a numerical simulation. In their study, the design consisted of a 4 cm × 4 cm × 0.5 cm aluminum plate joined to a 1 m-long aluminum rod. This rod was covered by a 590 mm long heat insulator to minimize heat exchange with the asphalt. Their study included the verification of the influence of different parameters to optimize the conception of the harvester. Additionally, the geological layers were assumed to be horizontal, and their properties were uniform to save computational time. Consequently, a 2D simulation can fulfill the numerical approach without losing the precision of the design. Figure 9 shows the conception and the components of the proposed harvester.

For the conception of a thermoelectric harvester, the choice of the materials to use is a major concern. Twaha et al. [99] reviewed the materials and performance of thermoelectric technology. The figure of merit indicates the performance of the material. Consequently, a larger figure of merit allows us to obtain a higher thermoelectric efficiency of the material. In addition, lower thermal conductivity and higher electrical conductivity are required to obtain a higher ZT. It was found that the ZT of these materials varies by approximately 1.0.

4.2.2 Experimentation and validation

Jiang et al. [96] conducted experiments on an RTEGS prototype. The experimentation consisted of preparing an asphalt mixture slab of 300 mm × 300 mm size. Then, three TEG-199 devices were used to transform the thermic energy into electrical energy. The cold part (water tank and heat sink) was covered in a shading board to avoid excessive exposure to sunlight.

The experimentation tests of the RTEGS [96] showed two relevant results. Both were obtained with an asphalt composition (300 mm × 300 mm size). Depending on the season, the output voltage may vary. In the winter, an output voltage of 0.4 V was observed when the temperature gap between the road surface and ambient temperature was 15 °C. In summer, the generated voltage varied from 0.6 to 0.7 V, with a temperature gap varying from 25 to 30 °C. By extending these results, in the case of a road of 1000 m × 10 m, the harvested energy can reach 160 kW for 8 h exposition [96].

Another paper by Jiang et al. [100] detailed the temperature-reduction functions of the RTEGS. It was found that in the summer, the proposed RTEGS can diminish the road surface temperature from 8 to 9 °C in June and July. In winter, a temperature reduction of approximately 5 °C was observed from February to March. Their study [100] demonstrated the variation in the temperature reduction compared to the temperature of the road. Thus, the work of Jiang et al. [100] indicated that there is a limit in the temperature reduction functions of the RTEGS due to the limited conversion capacity of the system.

Dutta et al. [95] developed an experimental prototype of a thermoelectric energy harvester. Their study also analyzed two larger TEGs and four smaller TEGs, and the cost of the system was assessed. As a result, the cost of the two TEGs was $94, while the cost of the four TEGs was $190 without the installation cost. Finally, Dutta et al. [95] reported that the two-TEG prototype generates 8 mW, while the four-TEG prototype could produce 11 mW. Thus, the use of multiple TEGs can be interesting for generating higher energy with their prototype.

In the work of Tahami et al. [97], the field testing of the proposed prototype was then performed in the temperate zone of South Texas. After the design process, the prototype was created and tested to verify the expected power generation. For this purpose, a 60 mm thick asphalt mix slab was made in the laboratory. The heat conveyor (copper) was placed at 30 mm deep on the asphalt surface to capture heat. The temperature data were collected by temperature sensors at four points. Ultimately, after optimization, their proposed prototype can produce 29 mW. Connecting the TEGs in series and forming an array would allow the system to reach higher harvested power [97]

The depth of the installation of the thermoelectric generators is an important parameter for the amount of harvested energy. The study of Jiang et al. [101] concluded an ideal depth of 20–30 mm for their experimental prototype because it leads to an acceptable temperature difference between the asphalt surface and the thermoelectric generators (3–4 °C of temperature difference). However, existing studies are experimental prototypes, focused on the maximisation of the harvested energy. The impact of the installation of harvesting systems on the structure is not widely included in the existing literature. Practically, installing TEG at 20–30 mm depth will affect the structure of the roadway, especially when some metal (copper or aluminium) are inserted under the surface of the asphalt mixture to conduct the heat to the TEG [101–103]. The heat from the exposition to the solar radiation will dilate and deform the surface of the roadway, and the inserted metals could disturb the uniform dilation and deformation of the asphalt structure. Though, one of the benefits of using thermoelectric technology is the mitigation of the urban island effect [104]. The temperature of the surface of the road will decrease if TEG systems are installed. Another study by Jiang et al. [100] reported a peak temperature reduction of 8–9 °C by the use of their road thermoelectric generator system (RTEGS). Thus, this temperature reduction may also reduce the impact of the dilation and deformation of the roadway structure due to heat. But further studies are needed to understand and measure the real impact of the installation of harvesting technologies in the roadway structure.

Notably, the current thermoelectric technologies provide higher electrical power than piezoelectric technologies. In the literature, the work of Tahami et al. [97] presents a higher power density (3.02 mW/cm^3) compared to the other proposed systems (1.457–2.83 mW/cm^3). However, studies regarding its application on roadways are still limited compared to piezoelectric technologies. In only a few existing studies, the levelized cost of energy (LCOE) is discussed. However, given the current state of these studies, thermoelectrical technologies are still not competitive compared to conventional energy sources. In addition, deeper studies regarding the integrity of the roadway structure combined with a thermoelectric energy harvester are missing from the current literature. To enhance the electrical outputs of these harvesters, future research should focus on the following approaches:

- the improvement of thermoelectric material properties
- the disposition of the harvesting system to maximize the temperature gradient
- the improvement of the pavement structure properties

In addition, the design and construction process of the pavement structure will play an important role regarding the pavement properties [105, 106]. Future research must pay attention to this factor and consider it during their work.

5 Piezo-thermoelectric Coupling Harvesting Approaches

Harvesting energy from roadway pavements commonly consists of the conversion of mechanical vibration, thermal gradients, or other sources of ambient energy into electrical energy. Most of these studies are based on only one of these sources to convert energy. The combination of mechanical vibrations and thermal gradients is thus a new way to explore this field. This combination forms a hybrid harvesting system that can solve the problem of intermittent energy and boost the extracted energy. In this section, most of the presented approaches were not designed to harvest energy from roadway pavement. However, these approaches can be adapted to the conditions of roadway pavement to develop new models.

5.1 Designing and Modeling

The design of a harvester system is primarily related to its application. Some design processes are made for human applications. For instance, Oh et al. [29] designed a bendable hybrid harvester to convert heat and human motion into electrical energy. In their study, piezoelectric and thermoelectric phenomena were exploited together. The energy from kinetic motion is collected by the piezoelectric portion, while the thermal energy is collected by the thermoelectric portion.

Two piezoelectric cantilevers and two permanent magnets compose the piezoelectric part, while eight p-type thermoelectric materials represent the thermoelectric part.

Yoon et al. [107] designed an energy harvesting circuit that also exploits thermic energy and vibration. In their paper, a double pile-up mode circuit was proposed to exploit the mechanical energy by increasing the damping force. In addition, a boost converter model was developed. Electrical models of both the piezoelectric transducer and thermoelectric generator were then included to simulate the behavior of the harvester circuit, as shown in Fig. 10.

The installation of the TEG and RETG systems does not need to be performed directly under the vehicle wheel path. Ideally, to protect the system, it should be installed between the wheel paths and the side of the road pavement lane. This placement will still provide adequate access for vibration and heat to be gained by the sensor while protecting the system against continuous tire loading.

The piezoelectric transducer is modeled as an AC source, while the thermoelectric generator is modeled as a DC source. Four controlled switches (SW1, SW2, SW3, and SW4), a single-shared inductor (L_{ind}), enable their harvester to operate in both double pile-up mode and boost converter mode through a time-multiplexing method. A notable improvement is then advanced by Yoon et al. [107] about this circuit compared to the basic full bridge rectifier: in their study, the power extraction of the harvester circuit is

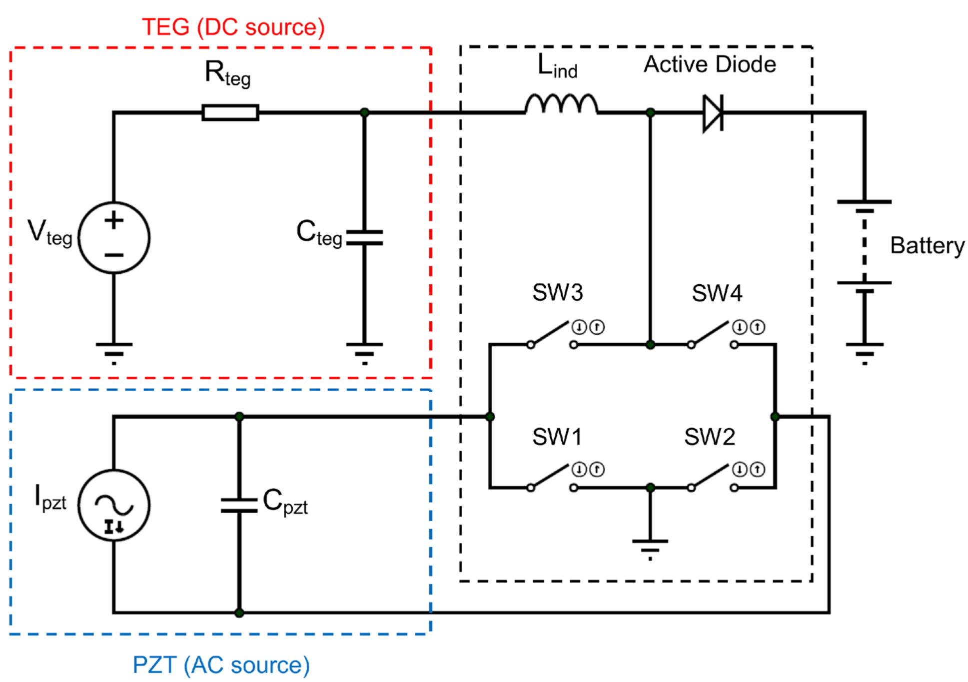


Fig. 10 The Yoon et al. harvester circuit [107]

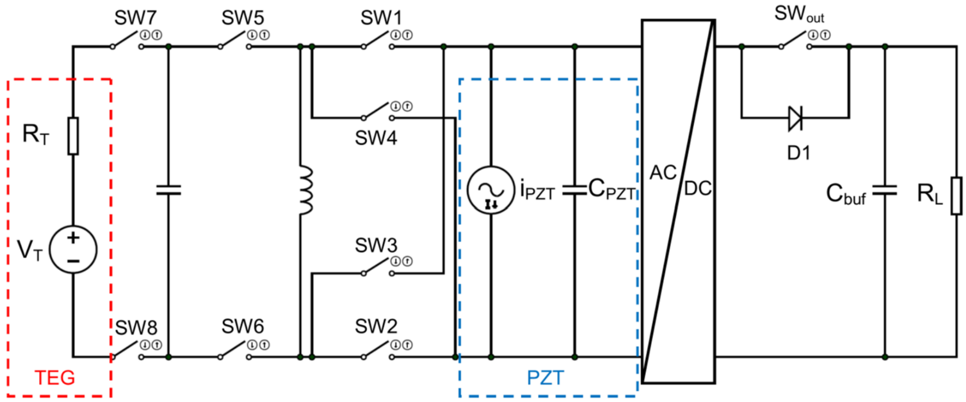


Fig. 11 The Li et al. harvester circuit [108]

1452% higher than the full bridge rectifier. In addition, their harvester achieves 75% conversion efficiency with 450 µW output power. The harvested energy is thus used to charge a battery from both vibration and thermal energy sources as well as other low-powered multiple energy sources.

Li et al. [108] designed an interface circuit for piezoelectric and thermoelectric energy harvesting. In their study, electrical models of both piezoelectric and thermoelectric devices were conceived to run a simulation. The harvesting circuit related to those devices consists of a novel inductor based on a parallel-SSHI (synchronize switch harvesting on inductor) structure, as shown in Fig. 11.

Their study assumed that the vibration excitation is sinusoidal, and as a result, the piezoelectric transducer was associated with a sinusoidal current source mounted in parallel with a resistor and a capacitance. In addition, the thermoelectric generator was associated with a DC voltage source mounted in series with a resistor. This time, eight controlled switches were used (SW1, SW2, SW3, SW4, SW5, SW6, SW7, and SW8) with a shared inductor (L_p). An AC/DC converter was also used before feeding the load resistance (R_L).

Dessai et al. [109] also conducted a simulation of a hybrid energy harvester. The proposed method uses the maximum power point tracking (MPPT) algorithm with a DC–DC boost converter. Depending on the inputs, the MPPT control circuit adjusts the duty cycle of the DC/DC converter. As a result, the energy harvester circuit ensures that the output voltage remains stable with better impedance matching. Maximum power is thus harvested.

Jella et al. [36] studied the design of a new harvester based on the use of methylammonium lead iodide $MAPbI_3$ and interdigitated electrodes. The proposed system can exploit thermal, mechanical, and solar energy in a single configuration using $MAPbI_3$. Furthermore, the device used as a piezoelectric generator delivers 1.47 V and 0.56 µA under periodically applied pressure.

Zhou et al. [110] proposed an energy harvester using thermo-electromechanical couplings. The corresponding circuit was also studied in their paper. The hybrid harvester was designed for waste energy harvesting in the field of fluid flows. An experimental prototype was fabricated based on the Brayton cycle system. This prototype consists of the integration of PVDF cantilevers for the piezoelectric part and Bi_2Te_3 for the thermoelectric part. A comparison between parallel and series disposal was also conducted to determine the best configuration. Lastly, their study showed the possibility of using a thermomechanical harvester. As a result, the length-specific power of the proposed harvester is approximately 55 µW/cm in the series configuration.

Kumar et al. [111] combined a thermoelectric module with a flexible piezoelectric film to compose a hybrid harvesting system. In their study, a simple chemical solution method was proposed to harvest electrical energy and obtain a small flexible device. Their paper reported an output power of 1.8 nW at a 4 °K temperature gap, while the piezoelectric nanogenerator delivers an open circuit voltage of approximately 4 V and generates 1.2 µW.

Abdal-Kadhim et al. [28] researched the hybrid energy harvesting scheme. In their study, piezoelectric and thermoelectric energies were combined to overcome single harvester drawbacks such as weak power, intermittence, and inconsistency. For the two typologies, a full-wave bridge rectifier combined with a smoothing capacitor rectifies the piezoelectric output, while a DC-DC boost converter boosts the thermoelectric output to 5 V. Parallel and series typologies were tested by charging a capacitor bank of 15 mF up to 5 V. The time required to charge the capacitor fully is then compared for the two typologies. Figure 12 shows the parallel and series typologies.

I_{TEG} and V_{TEG} represent the current and the tension from the thermoelectric generator, respectively, while I_{PIEZO} and V_{PIEZO} represent the current and voltage from the piezoelectric generator, respectively. For the parallel typology of the hybrid harvester, the electrical current from thermoelectric and piezoelectric generators are added according to the relation:

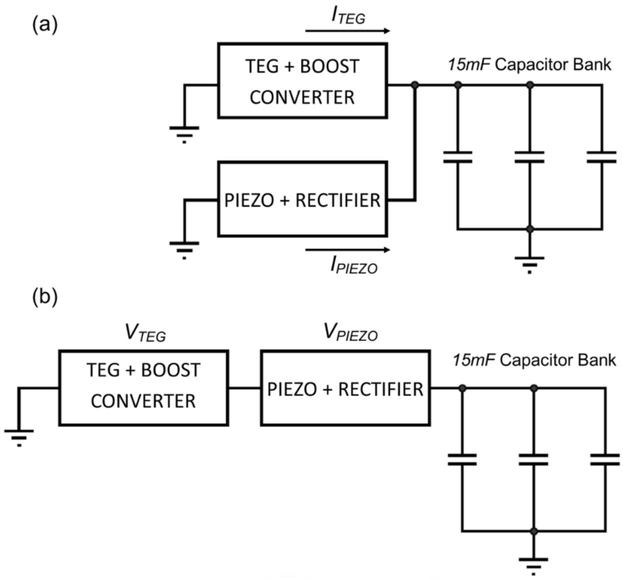


Fig. 12 Schematics of the hybrid harvester for parallel (**a**) and series (**b**) topologies [28]

$$I_{\text{Hybrid}} = I_{\text{TEG}} + I_{\text{PIEZO}}. \tag{12}$$

The overall voltage of the hybrid harvester in the series topology is the combination of both thermoelectric and piezoelectric harvester voltages according to the relation:

$$V_{\text{Hybrid}} = V_{\text{TEG}} + V_{\text{PIEZO}} \tag{13}$$

Montgomery et al. [112] also studied the combination of bendable thermoelectric and piezoelectric materials into a single tool. The aim of their research is to optimize the efficiency of the coupled power output of the hybrid harvester and overcome issues about traditional thermoelectric and piezoelectric generators. The proposed device was designed using a carbon nanotube/polymer (CNT) thin film for the thermoelectric part, while PVDF was used for the piezoelectric part. Then, an electrode from the piezoelectric film was positioned on the top electrode, and an interchanging n- and p-type thermoelectric was placed as the bottom electrode. The hybrid device is also bent at p-n-type junctions, and a thermal gradient is thus formed through the width of the device.

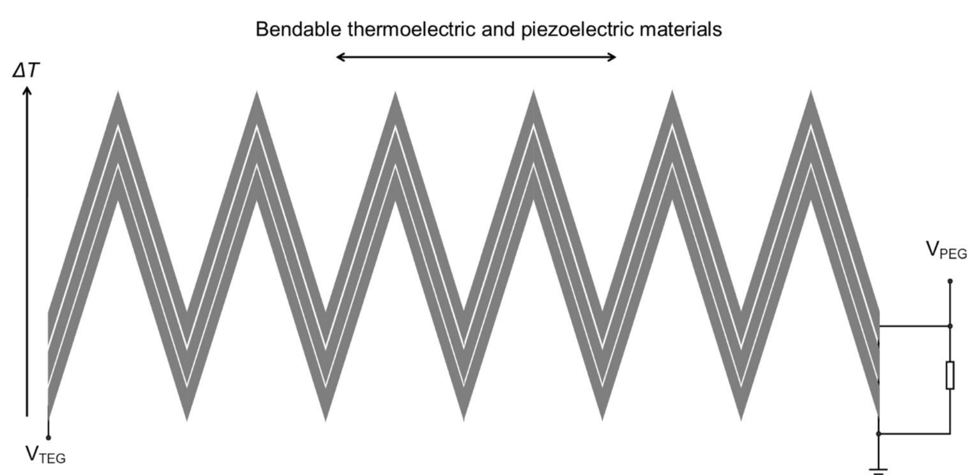
The thermoelectric voltage (V_{TEG}) is evaluated from the common ground to the opposite side (both on the bottom), while the piezoelectric voltage (V_{PEG}) is determined among the top and bottom electrodes, as seen in Fig. 13.

Dorey [113] reviewed piezoelectric and thermoelectric powder-based thick films for harvesting energy. His paper reported that the current harvesting instrument uses semi-manual fabrication approaches and leads to greater costs. Additionally, the efficiency of these current devices is reduced and presents significant material wastage. Then, the most commonly used technologies were reported to integrate piezoelectric and thermoelectric harvesters into a thick film. The thickness of the films may vary from 2 to 200 µm. In this range, the films have better potential for use in the field of energy harvesting applications. As a result, his study concluded that it is possible to manufacture piezoelectric and thermoelectric thick films with a power density of 100–1000 µW/cm^2.

5.2 Experimentation and Validation

Oh et al. [29] conducted experimentation on their hybrid harvester. As a result, the power density of the piezoelectric part reaches 28.57 µW/cm^2, while that of the thermoelectric part reaches 0.64 µW/cm^2 with a temperature gap of 9.2 K. According to the design of their flexible harvester, applying this harvester to the knees and elbows of the human body was an ideal use. The heat and vibration from the body could thus be converted into electrical energy [29]. Even if the power generated by the thermoelectric element is less than the piezoelectric part, the advantage of this hybrid system is that the heat can be harvested continuously to maintain the energy supply when

Fig. 13 Voltage measurement of Montgomery et al.'s harvester [112]



there is no stable vibration. The application of this system in pavement harvesting can be very interesting with further adaptation to roadway conditions.

The experimental results of Abdal-Kadhim et al. [28] on the comparison between the parallel and series configuration of a hybrid harvester have shown that the parallel typology takes 27 s to charge the 5 V, 15 mF capacitor bank fully. However, the charging time required to charge that 5 V, 15 mF capacitor bank fully for series is approximately 20 s because the combination of the voltage from the two sources in a series typology is more consequential than the combination of the current from the hybrid harvester. As a result, higher charging power is delivered by the series typology according to the following relation:

$$P = I * V. \tag{14}$$

Thus, their study [28] showed that piezoelectric and thermoelectric generators arranged in series topology can charge a capacitor faster than those in parallel typology. In their research on a hybrid thermoelectric piezoelectric generator, Montgomery et al. [112] conducted experimentation on their harvester. Their study reported that a 2×2 array of the proposed harvester can generate 89% of the maximum thermoelectric power. In addition, the piezoelectric voltage is 5.3 times better than that of a traditional device.

Goudarzi et al. [114] used parallel and series SSHIs to harvest energy from vibration and thermal gradient sources. In their paper, a comparison between these SSHI methods was conducted. The use of parallel SSHI was found to allow for better energy harvesting.

Table 2 summarizes the existing hybrid piezo-thermoelectric energy harvesting technologies in the literature. The materials, electrical outputs, and conclusion of each study will be compiled to provide a better understanding of these studies.

Even if the existing studies are not especially concerned with pavement applications, according to the available literature, the electrical outputs from combining two energy harvesters are interestingly higher than those of only one energy source. However, most existing studies on piezo-thermoelectric hybrid energy harvesting systems are focused on electrical modeling and simulation. The disposition and impact of these harvesting systems on the environment are thus missing to evaluate the potential of these systems. Real experimentation will be needed for future research to address this aspect. These experiments can also be applied to pavement, and the impact of embedding energy harvesters in the pavement structure must be evaluated. However, the existing studies do not include cost assessments; thus, deeper cost studies are needed in future research to understand the economic viability of the system. Lastly, the piezoelectric harvester is modeled as an alternating current generator, while the thermoelectric harvester is modeled as a direct voltage generator. The design of the electronic circuit according to this combination can also enhance the electric outputs of the hybrid system. This consideration will be another significant aspect of future research in this field.

6 Discussion on the Cost of Energy Production Systems

The interest in energy harvesting is increasing considerably, so many techniques and technologies are being developed. Comparing these technologies include analyzing several parameters mostly energy output and the cost. The energy output determines the potential of the technology while the cost determines its economic viability. However, these two parameters depend mainly on the level of the technology. The Technology Readiness Level (TRL) [115] is a score attributed to a technology that indicates how mature and ready it is for large use. This score may vary from 1 to 9. A TRL of 1 means the technology is not yet mature, only basic concepts and limited observations are reported in scientific papers. On the other hand, a TRL of 9 indicates that the technology can be widely used in an operational environment. Wang et al. [116] reported a TRL of 3–4 for piezoelectric and thermoelectric harvesting systems in the roadway. Jiang et al. [101] indicated a TRL of 5–6 for their thermoelectric generators system. Concerning the cost of energy, a reliable and universal method should be used to compare energy systems. The most used concept is the Levelized Cost Of Energy (LCOE). The LCOE is an approved idea to evaluate and compare different energy systems. It takes into consideration the cost of energy even if the compared technologies have unequal life spans and unequal ranges of energy production. The calculation of the LCOE requires knowing the total cost of the energy production including the construction and installation of the energy system, the cost of the maintenance during its life span, and finally the cost of the removal of the system at the end of the system's life. Practically, only construction and installation of the system are taken into consideration in a roadway energy harvesting system because it is still in development without real-scale application and there is no further studies about its life cycle. The calculation of the LCOE also requires knowing the total energy production of the system during its entire life span. Thus, the LCOE of a system is the cost of the energy during its life span (in dollars) divided by the energy produced during its life span (in kWh), as seen in Eq. (15).

$$\text{LCOE} = \frac{\text{Total cost over lifespan}}{\text{Total energy production over lifespan}} \tag{15}$$

Table 2 Hybrid piezo-thermoelectric harvesting system advances

Authors	Main study	Materials	Outputs	Study conclusion
Goudarzi et al. 2013 [114]	Electrical modeling, harvester circuit and simulation	PZT/PMN-0.25PT, series and parallel SSHI	Max power: 8.335 mW	Hybrid energy harvesting increases 53% more power than only piezoelectric harvester
Dessai et al. [109]	Electrical modeling, harvester circuit and simulation	MPPT control circuit/MATLAB-Simulink software	Piezoelectric max power: 1.6 mW/ thermoelectric max power: 313 µW/ Hybrid max power: 1.84 mW	MPPT and DC/DC boost converter allow impedance matching and higher power extraction
Montgomery et al. [112]	Desing and experimentation	15 wt% CNT (carbon nanotube)/85 wt%PVDF	TEG voltage: 3.1 mV at 10°K/PEG voltage: 18.1 mV	The structure of the system provides optimal thermoelectric performance and enhances the output voltage in the piezoelectric part
Yoon et al. [107]	Electrical modeling, harvester circuit and simulation	Piezoelectric product: Mide PPA 1001 with double pile-up resonance technology	Max power: 450 µW with a peak efficiency of 75%	The energy collected from the described circuit is 1452% higher than that collected from a full-bridge rectifier
Jella et al. [36]	Design and experimentation	Use of methylammonium lead iodide ($MAPbI_3$) and interdigitated electrodes (IDEs)	Max piezoelectric outputs: 1.47 V and 0.56 µA/Max Seebeck coefficient: 107.93µV/K	The structure of the interdigitated terminals in transport layers enables the system to collect thermoelectric, piezoelectric, and solar energy
Oh et al. [29]	Design and experimentation	Piezoelectric part : PVDF/Thermoelectric part: Sb_2Te_3 (in powder form) and conductive polymer PEDOT:PSS	Piezoelectric power density: 28.57 µW/ cm^2/Thermoelectric power density: 0.64 µW/cm^2 at 9.2 K of temperature difference	Harvester is suitable for the knees and elbows of human body. Constant thermal source of human body provide sustainable energy
Li and al. [108]	Electrical modeling, harvester circuit and simulation	Piezoelectric product: Mide PPA 1014 with improved SSHI technology	Max power: 421.2 µW with direct contribution of TEG at 2.17%	The described circuit can harvest 15.8% higher energy than the conventional SSHI rectifier with a 10KΩ load resistance
Kumar et al. [111]	Design and experimentation	Piezoelectric part: ZnO-PVDF film/ thermoelectric part: (n-Bi_2Te_3 -RGO)–(p-Sb_2Te_3-RGO)	Ma piezoelectric power: 1.2 µW/max thermoelectric power: 1.8 nW	Combining many thermoelectric components in series can increase the energy generation of the harvester. Use the hybrid system in an environment where both heat and vibrations are available
Abdal- Kadhim et al. [28]	Electrical modeling, harvester circuit and simulation	Piezoelectric part: fullwave bridge rectifier/thermoelectric part: DC–DC boost converter	Charging time required to fully charge 5 V and 15 mF capacitor: 27 s for parallel typology and 20 s for series typology	A slight difference is observed between series and parallel topology for the same hybrid scheme. The series topology is better than the parallel topology about charging capacitor
Zhou et al. [110]	Design and experimentation	Piezoelectric part: PVDF cantilevers/ thermoelectric part: Bi_2Te_3	Length-power density: 55 µW/cm according to a temperature gradient of 4 K	Piezo-thermoelectric hybrid generator enhances the use of waste heat energy by 38% than an only thermoelectric harvester

Table 3 Comparison of energy harvesting technologies [116]

Technology	TRL	LCOE ($/kWh)
Thermoelectric [25]	3	95.74
Piezoelectric [117, 118]	4	106.387
Electromagnetic [119, 120]	4	278.95
Solar collectors [92, 121]	4	4.21
Photovoltaic [122, 123]	9	0.45
Geothermal [124]	9	0.1561

Concerning roadway energy harvesting systems, the LCOE can be calculated for one lane mile roadway to allow a better understanding of the scale. Wang et al. [116] have compared different energy harvesting technologies, as reported in Table 3.

It is observed that the cost of energy varies according to the TRL. A mature technology with a higher TRL usually has a lower cost of energy. Whereas a less mature technology with a lower TRL costs higher. The TRL of photovoltaic technology is 9, consequently its LCOE is very low (0.45$/kWh). On the other hand, the TRL of thermoelectric technology is 3 and its LCOE is higher (95.74$/kWh). Some technologies are mature with a high TRL because they were developed and optimized for cost-effectiveness for decades before being widely used, as photovoltaic. Piezoelectric and thermoelectric harvesting technologies are still in the prototype phase with a low TRL, so their cost-effectiveness are not yet optimized enough. Compared to conventional electricity production systems, roadway energy harvesting systems are more expensive. Most of conventional systems were developed decades ago, and are already widely used in the world (hydropower, wind, solar PV,...). Their costs were already optimized and are lower compared to roadway energy harvesting technologies. However, the cost of different systems using the same technology may vary due to the environment and initial condition of the systems. The calculation of the LCOE may also vary according to the input data used for the study. Tran and Smith [125] have summarised the LCOE of different energy sources as reported in Table 4.

It can be noticed that the LCOE of these mature energy sources is lower compared to roadway harvesting technologies. This fact also demonstrates the increasing interest in harvesting systems to optimize them and eventually reach the same TRL and LCOE of widely used conventional energy sources. It can be noticed that the LCOE of these mature energy sources is far lower compared to roadway harvesting technologies. This fact also demonstrates the increasing interest in harvesting systems to optimize them and eventually reach the same TRL and LCOE of these widely used conventional energy sources. On the other hand, the application of the energy from harvesting systems differs from these conventional sources. The harvested energy is not mainly aimed to supply electricity to a city, but mostly to power small devices near them, for instance: monitoring devices, microelectronics, lights, etc.

Table 4 LCOEs of energy technologies with carbon pricing [125]

Technology	Mean ($/kWh)
Coal	3.0799
Natural gas	1.0411
Nuclear	0.6092
Solar PV	0.6181
Solar thermal	1.0908
Onshore wind	0.1358
Offshore wind	0.2959
Hydropower	0.5514
Biomass	0.467
Geothermal	0.2557

7 Conclusion and Discussion

According to current global warming concerns and fossil energy depletion, harvesting energy from roadway pavement provides a promising solution. This harvesting system can generate clean and renewable energy by converting thermal energy (from solar radiation) and mechanical energy (from vehicle loading) into electrical energy. Roadway pavements absorb heat from solar energy. This heat accumulation is considerable at high temperatures during the summer. Consequently, roadway pavement degradation and the aging of pavement materials are aggravated. Hence, converting this heat into electrical energy helps reduce the pavement temperature and recovers energy from along the roadway to be used. Additionally, the urban heat-island effect is increased by the absorption of heat by the pavement. Passing vehicles are also creating mechanical vibration into the pavement. For this purpose, piezoelectric transducers are employed to transform mechanical energy into electrical energy, while thermoelectric generators directly transform the temperature difference into an electrical voltage through the Seebeck effect.

This paper presents a comprehensive literature review about energy harvesting from roadway pavement, especially on piezoelectric and thermoelectric techniques. All of these energy harvesting techniques generate renewable and available energy, and roadway pavement can be transformed into an energy center. However, an analysis of the literature indicated that the advanced studies on the two technologies are different. There are several studies on piezoelectric harvesting systems, while there are limited studies about thermoelectric generators as applied to roadway pavement.

It was also found that most of the work on piezoelectric harvesting systems is more about electromechanical modeling, electronic simulation, and prototype design. Voltage and power density are taken into consideration in most studies. Different designs made of piezoelectric material have been developed in the literature for stress and vibration-based energy harvesting. As a result, the harvested energy output is commonly low for individual piezoelectric transducers (in the range of µW) for each passing vehicle. To generate a higher amount of energy, we should use multiple sensor arrays and apply this technology, especially where repeated traffic loading is observed. Additionally, a highway is more interesting for installing piezoelectric technology to have a higher speed limit, which includes higher harvested energy.

In the literature, most thermoelectric harvesting technologies are focused on structural design to obtain a maximum temperature difference. A higher temperature difference leads to a higher harvested energy and contributes to better UHI mitigation. However, the power generated from one thermoelectric generator is also in the range of µW. Additionally, the cost of harvested energy is relatively high for lower power generation compared to photovoltaic technology. However, the efficiency of the thermoelectric harvester can be improved by developing a better structure design for conducting to a higher temperature difference and for the development of material properties conducting to a higher Seebeck coefficient. Further studies can also propose a better electronic approach to improve DC/DC conversion.

Thus, other aspects, such as studying the cost efficiency of the proposed devices, should be more developed in further research. Additionally, the evaluation of the durability of the proposed system as well as maintenance planning and their impact on the pavement structure and performance, can be a major challenge in the concretization of piezoelectric and thermoelectric harvesting systems. Even if there are increasing studies in the field of roadway harvesting technologies, a higher power density should be obtained before a commercial application is created.

A review of hybrid energy harvesters was also conducted in this paper. These hybrid systems are not specially designed for roadway application, but they open a new path to this field. Hybrid harvester systems have not yet been developed in the field of pavement energy harvesting. Most of the studies are focused on only one source of ambient energy (thermal or mechanical vibration). Further research on extracting energy from heat and vibration through the design of a hybrid system is thus interesting. The combination of thermoelectric and piezoelectric elements increases the harvested energy. Combining these two sources of ambient energy to generate sustainable energy can be the best solution for research on pavement energy harvesting by providing sustainable and renewable energy. Further studies on hybrid harvesting systems to adapt and develop their use in roadway pavement must be conducted in the future. Future trials on these harvesters should include cost studies, life cycle assessments, and the impact on the roadway structure to complete the existing results.

Finally, energy harvesting technologies from the roadway can generate green and renewable energy without any gas emissions associated with their conversion process. These technologies contribute to diminishing the use of fossil energy sources. On a large scale, they can be used to supply roadside applications such as powering LED lights or microelectronic devices along roadways and powering roadside houses without transmitting electricity from conventional sources.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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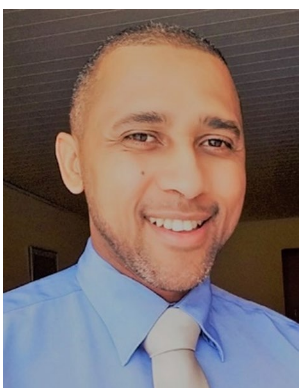

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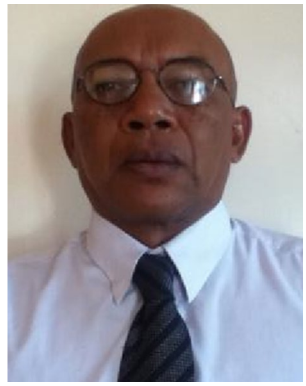

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