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ANALYSIS AND SYSTEMATIC LITERATURE REVIEW ON ENERGY HARVESTING FROM ROADS

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Abstract

*As the global warming crisis escalates, the demand for greener energy production methods becomes increasingly urgent and important. Energy harvesting has emerged as a key area of interest for researchers seeking innovative solutions. The goal is to eventually replace fossil fuels with renewable energy sources, which are non-renewable and the primary contributors to global warming. In this study, an analysis and systematic literature review are conducted on studies that presented ways of efficiently harvesting energy from roads. This study will focus on three energy harvesting techniques (Thermoelectric, Piezoelectric, and Electromagnetic) and propose future research directions in energy harvesting from roads, including exploring new materials and technologies. The study will also suggest novel solutions to issues relating to energy harvesting from roads, such as improving the construction and installation of energy-harvesting systems and creating innovative materials and cost-cutting methods.***

***Keywords**: energy harvesting, power generation, renewable energy, piezoelectric, thermoelectric, electromagnetic.*

1. INTRODUCTION

The primary cause of global warming is the continual use of fossil fuels, which contribute more than 70% of all greenhouse gas emissions into the atmosphere [1]. The transportation sector is the sector with the second-highest energy use, and road transportation generates about 75% of carbon dioxide emissions in the transportation sector [2]. In 2007, it was estimated that fossil fuels made up 85% (comprising 27% coal, 35% oil, and 23% natural gas) of global energy consumption and contributed to 68% of the world's electricity production. On the other hand, renewable energy sources, known for their environmental friendliness and potential for sustainable utilization, accounted for 10% of total energy consumption and 18% of global electricity generation during that year [3]. Figure 1 shows the world's fossil fuel consumption measured in terawatts-hours, with oil accounting for over 52000TWh in 2022.

Energy harvesting is the conversion of ambient energy present in the environment into other useful means, such as electrical energy. Since the authors in [4] originally presented the idea of transforming vibration energy into electrical energy, research on the electrical conversion of vibrating micro-energy has been more important. The concept of energy harvesting has recently been adopted in the field of renewable energies in addition to the major energy sources, making it possible to produce electrical energy from minute energy variations like thermal gradients, vibrations, and electromagnetic radiation. Roads provide energy that is ready to be harvested and converted into a usable type of energy, i.e., electrical energy, thereby reducing the need to import energy from distant locations [5]. Energy harvesting from roads offers a potential answer to obtaining energy from renewable resources in conjunction with the rising demand for renewable energy sources to lower greenhouse gas emissions.

This paper presents a systematic literature review of the various sources of energy that can be harvested from roads and performs a comparative analysis of the viability of each approach while evaluating the latest advances in road energy harvesting, considering the technologies used their effectiveness, and their limitations. The aim is to propose future research directions in energy harvesting from roads, including the exploration of new materials and technologies. For these technologies, the following elements from past research papers will be investigated. The type of technology material used in each research, the type of road infrastructure i.e., road surface, underground pipes/cables, the different design and placement of the electromagnetic, thermoelectric and piezoelectric devices and how much energy is harvested, and the energy storage system used. The remainder of this paper is organized thus – Section 2 details the methodology employed in this study, while Section 3 presents the results obtained. In Section 4, the discussions arising from the findings are presented, while Section 5 summarizes and concludes the paper.

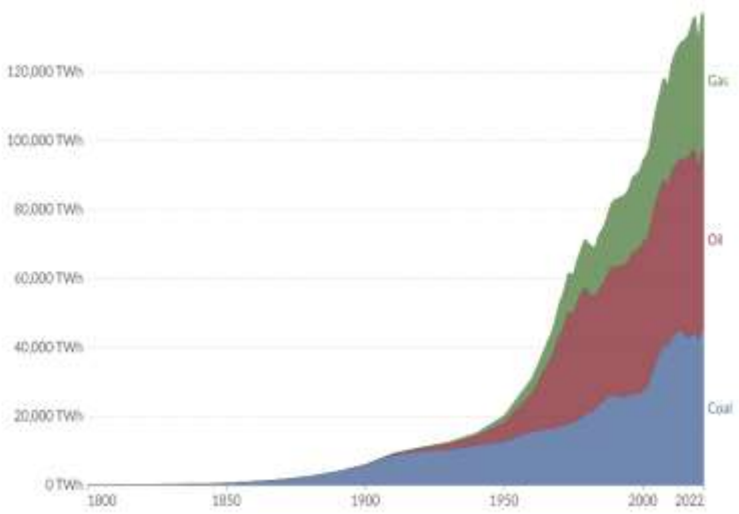


Fig. 1: World’s fossil fuel consumption by fuel type in TWh. Data Source: Energy Institute – Statistical review of world energy (2023) [1]

2. METHODOLOGY

To carry out the analysis and systematic literature review of this work, a methodology from [6] is utilized. The method has six steps to follow when conducting a systematic literature review. The first step is the “Protocol” step, in which the research scope and formulation of the research questions and boundaries are identified. The key research questions for this work are:

1) What is the state-of-the-art Energy Harvesting Techniques (EHT)?

2) Which EHT had the highest and the least number of studies?

3) What are the diverse development trajectories and gaps in the sustainability of EHT?

4) What are the current challenges impairing EHT studies?

The second step is the “Search” step; the search strategy aids in the definition of appropriate search terms and the identification of appropriate databases for the collection of relevant documents. The search databases for this study are ACM Digital Library, ScienceDirect, IEEE Xplore, Scopus, and Google Scholar.

The next step is Appraisal, where chosen articles are assessed in accordance with the goal of the review process. To find relevant papers, two fundamental principles were followed:

Table 1 Article sources and the number of articles found

Article source	Number of articles
Scopus	18
ACM Digital library	5
ScienceDirect	59
IEEE Xplore	6
Google Scholar	10

Table 2 Breakdown of the article in the three forms of energy harvesting techniques

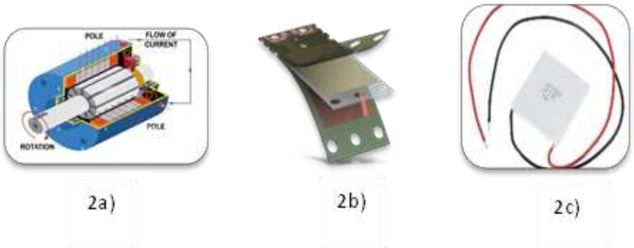
Article source	Number of articles
Thermoelectric	9
Piezoelectric	15
Electromagnetic	10
Mixed Technique	12
Total	**46**

1) **Exclusion-inclusion criteria:** In the course of applying this principle, inaccessible articles, meta-data, non-English language papers, and non-original articles have been excluded from the review, with a special focus on papers published between 2010 and 2024. **Error! Reference source not found.** below shows the number of articles obtained in each domain.

These papers drafted above encompass various types of energy harvesting techniques, but in this study, the focus is on Thermoelectric, Piezoelectric, and Electromagnetic energy harvesting techniques, other energy harvesting methods like Photovoltaic, Pyroelectric, and wind energy harvesting techniques were omitted. After performing the omission, only 59 articles were left to be assessed. In the process of analyzing various papers and articles, duplicate ones and those papers without clear assessment methods for thermoelectric, piezoelectric, and electromagnetic energy harvesting techniques were manually removed. Eventually, 46 publications remained that fulfilled all the necessary requirements to be included in this review. The breakdown of the articles for the remaining 3 forms of EHT is shown in **Error! Reference source not found.**.

2) **Quality Assessment:** This is carried out to ensure the quality of this work is maintained at a high level. The papers gathered are ensured that they have concrete evidence to back up the research work done and have a clear focus on the topic area. This was ensured throughout the quality

assessment and that the exclusion-inclusion criteria given were adequate, the literature search contained all relevant studies, and only peer-reviewed articles were included for evaluation.



2a) 2b) 2c)

Fig. 2a: Electromagnetic generator, **Fig. 2b:** Piezoelectric Material. **Fig. 2c:** Thermoelectric generator [7].

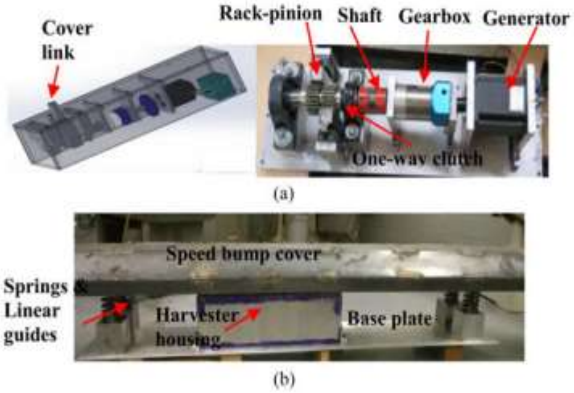
In the "Synthesis" stage, the papers were categorized as per the 3 major EHT; for this arrangement, consideration was given to the specific criteria that were utilized in the prototype's design and construction as well as the technique used to evaluate and quantify its performance. The information related was then retrieved and entered on an Excel spreadsheet for data processing and for further analysis, with the results shown using graphs and other types of charts. Following the "Synthesis" stage is the Analysis, where the evaluation of synthesized data and the extraction of meaningful information and the conclusion of the selected papers are conducted, and the formulated research questions are answered. It includes both the qualitative and quantitative interpretation and narrative of the results, as well as giving suggestions for future directions for research projects and drawing conclusions. Then lastly, the Report stage, which includes the description and presentation of the methods followed, and results obtained from the selected EHT articles.

3. RESULTS

In a review by the author in [8], they explained in a nutshell that these energy-converting devices are called electromagnetic converters because an electromagnetic engine is spun by the mechanical displacement of road pavements. Thermoelectric generators produce an electrical voltage when their bodies experience a temperature gradient, piezoelectric materials can transform mechanical vibrations into an electrical potential, and solar panels are widely recognized for their ability to convert solar radiation into electrical energy. These techniques can be seen in Figure 2, which depicts an illustration of the three types of harvesting techniques featured in this work.

A. Electromagnetic Harvesting Techniques

Electromagnetic generators are the core of the electromechanical conversion systems. They are used in numerous systems, including water and wind turbines. They are made up of a permanent magnet and a coil rotor. As soon as the coil rotor begins to rotate, it produces an electric field together with a time-varying magnetic field that follows Faraday's law. In terms of harvesting energy from road due to electromagnetic technology, the electromagnetic technology operates when a vehicle crosses the prototype; the vehicle's weight generates kinetic energy, which causes internal mechanical components to move. There are several types of system components that may be employed in the conversion process of vertical motions induced by a vehicle to rotate shafts within a generator. These components include rack-and-pinion systems, chain and sprocket systems, and hydraulic power systems as shown in Figures 3a and 3b [9].



(a)

(b)

Fig: 3 (a). Harvester design and prototype. **Fig: 3 (b).** Assembled Speed breaker energy harvester

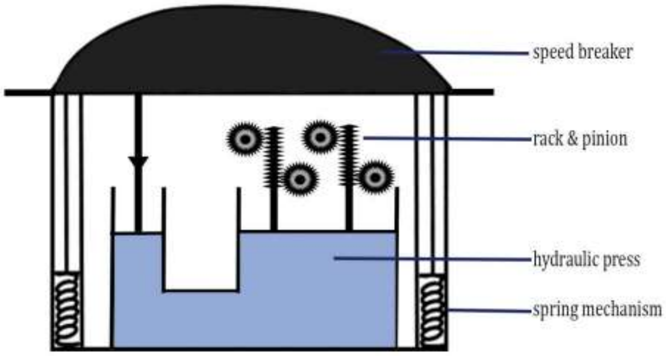


Fig. 4: Electromagnetic speed breaker mechanism

There are several electromagnetic prototype designs that have been documented in literature. In the work in [10], the authors created a speed breaker energy harvester (SBH) as shown in **Error! Reference source not found.**, which consists of two primary components: a cover portion of 2.74 metres in length and 0.36 metres in breadth that is placed on the ground to support passing vehicles, and an energy harvester part that turns up-and-down vibration into electrical energy. Four springs support the speed bump cover, enhancing energy regeneration when the cover returns to its initial position.

The harvester prototype is made up of one shaft, two pairs of rack-pinions, two one-way clutches, a geared generator, and a cover link rod. The cover link rod is fastened to the speed bump cover using racks to drive the pinions' rotation. Due to the engagement and disengagement of two one-way clutches positioned on the input shaft, the generator will always spin in a single direction regardless of the rack's direction of travel. Their in-field test showed that at lower vehicle speeds, one of the three phases may regenerate up to 647 W of peak power.

The work in [11] conducted research on the production of electrical power using a speed breaker. In the study, the speed breaker with a height of 15 cm is pushed to move downwards by vehicle pressure, which is transformed into rotational energy via a rack and pinion using a hydraulic press, which increases the force applied in the speed breaker by 4 × times from forming a small to large piston with 2 rakes attached to it. They estimated the power output of the speed breaker using calculations when a 350 Kg vehicle passes through the speed breaker, a power of 8.58 W is generated.

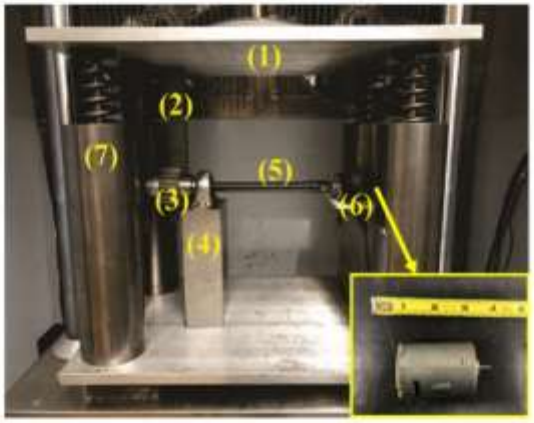


Fig. 5: The prototype for an electromagnetic system with top plate pinion^1 and clutch^2, Rack^3, Support shaft^4, Shaft^5, Shaft power source^6, spring and support^7

In a research conducted by [9], the authors created a speed bumper system prototype with a top plate made of aluminium with height and maximum displacements of 75 mm with width and length of 300 mm and 440 mm, respectively. Subsequently, a rack is fixed to the upper plate so that it may move in tandem with it. The pinions are firmly fixed to the lower plate. During the vertical motions of the top plate, the rack meshes with pinion gears. The pinions convert these motions into rotations. Although the rack and pinion rotate in two directions, they only transmit one direction of rotation to the shaft because of two one-way clutches. Their findings indicated that the output power was around 3.21 mW for each axle that passed. A four-steel cylindrical electromagnetic system prototype is shown **Error! Reference source not found.**.

The authors in [12] improved their prototype on **Error! Reference source not found.** by including a gearbox to enhance the generator's input revolutions and magnify its number of spins, the maximum vertical movement of the top plate was increased to 90 mm, also mentioned that a set of springs with stiffness magnitudes of 20472 N/m was used for this prototype, and having a linear generator mechanism as displayed in **Error! Reference source not found.**. The Universal Testing Machine (UTM), a programmed device designed to imitate traffic conditions, was used to evaluate both prototypes. For rack-pinion mechanisms, the average power output is 1.2 W, whereas in linear generator mechanisms, it is 80 mW.

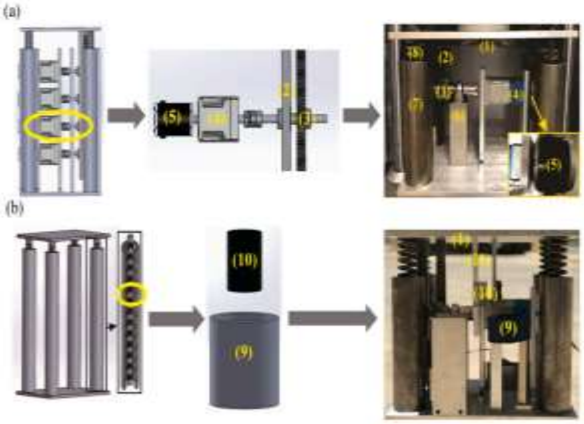


Fig. 6: The fabricated prototype (a) R-P mechanism with a Top Plate[1], Rack[2], Pinion and clutch[3], Gearbox[4], Generator[5], Pinion Support[6], Support[7], Compression Spring[8]. (b) L-GE mechanism with Electrical Coil[9], Set of Magnets[10], Rod[11].

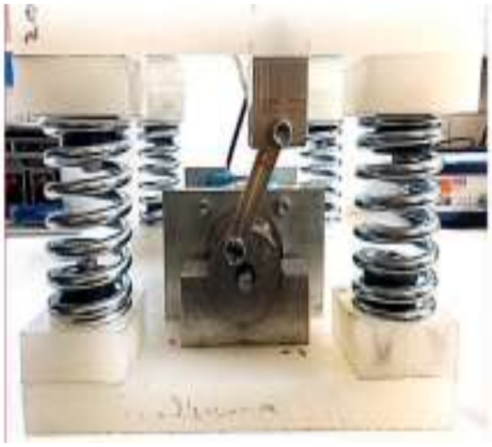


Fig. 7a: Mechanical harvester's model - front view.

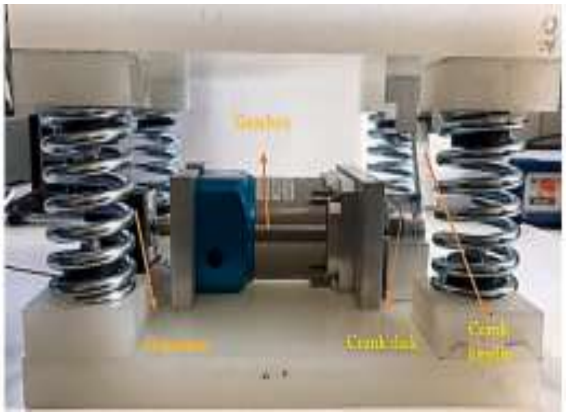


Fig. 7b: Mechanical harvester's model - side view

Another work by [13] outlined a novel electromagnetic road energy harvester that powers low-energy gadgets in smart cities with the least possible influence on traffic speed. Their harvester is based on a crank mechanism shown in **Error! Reference source not found.**a and 7b, during the experimental tests, five distinct spring sets were employed. They were 19.12 N/mm stiff, 25.2 N/mm stiff, 29.78 N/mm stiff, 37.88 N/mm stiff, and 43.54 N/mm stiff. Their aspect ratio was 1.78, which offers enough support to prevent buckling.

With a spring stiffness of 37.88 N/mm, the maximum average power of one cycle was 2.24 W, and the second-highest average power was 1.52 W, attained with a spring stiffness of 43.54 N/mm. In compliance with the study's goals, two LED lights were connected to the harvester's output and it was working at a loading speed of 14.67 mm/s with a cyclic load of 18 mm displacement. The LED lights are successfully powered by the harvester during loading and unloading. The bulbs were rated for 12 V and 2 W of electricity. The information in Table 3 below summarizes electromagnetic energy harvester technologies, their mechanisms and power output.

Table 3 Summary of Electromagnetic Energy Harvesting Technologies, their mechanisms and power output

Research	Mechanism	Type of testing	Cost	Power output
[10]	Rack and pinion	In-field test	--	647W
[11]	Rack and pinion using hydraulic press	Calculations	$1079	8.58W
[9]	Rack and Pinion	Lab Demonstration using UTM	--	3.21mW
[12]	Rack and Pinion with gearbox and linear generator mechanism	Lab Demonstration using UTM	$4000	1.28W
[13]	Crank mechanism with gearbox	Lab Demonstration	$1580	2W

B. Thermoelectric Energy Harvesting Techniques

When two pavement sections have different temperatures, thermoelectric technology may transform thermal energy into electric energy. A thermoelectric module's n-type and p-type legs allow electrons to flow freely across semiconductors and metals. The Seebeck effect and the Peltier effect, are the basis for the thermoelectric generation principles. Since roads are exposed to the sun, they collect a lot of heat that may be utilized for this purpose. When heat from asphalt pavement escapes into the surrounding air, the urban heat island effect worsens. High temperatures cause a significant decrease in the asphalt mixture's stiffness, which exacerbates pavement rutting [14].

It is consequently crucial to regulate the temperature of asphalt pavement and transform its thermal energy into various types of useful energy. Using the thermoelectric effect in asphalt pavement, damage from high temperatures may be mitigated and the road surface temperature lowered. The thermoelectric effect is explained, the temperature field of asphalt pavement is covered, and the designs of thermoelectric energy harvesting systems utilized in asphalt pavements are examined in a review by [14]. The research conducted for this review led to the conclusion that increasing TEG conversion efficiency and utilizing the maximum power point tracking algorithm in combination with a DC converter can boost the system's generating power for harvesting thermoelectric energy from asphalt pavement (SHTE-AP).

1) Thermoelectric Prototype Designs

A prototype that transfers thermal energy from the road's surface to a thermoelectric generator (TEG) module buried in the subgrade at the pavement's shoulder has been proposed by the authors in [15]. In the work, a Z-shaped thermally isolated copper plate and a thin, square TEG module are positioned between the copper plate and bottom heat sink, and a heat sink attached to the TEG's bottom makes up the prototype's four main parts as shown in Figure 8. The copper plate used in [15] was an elongated Z-shape metal with a thickness of 15 mm.

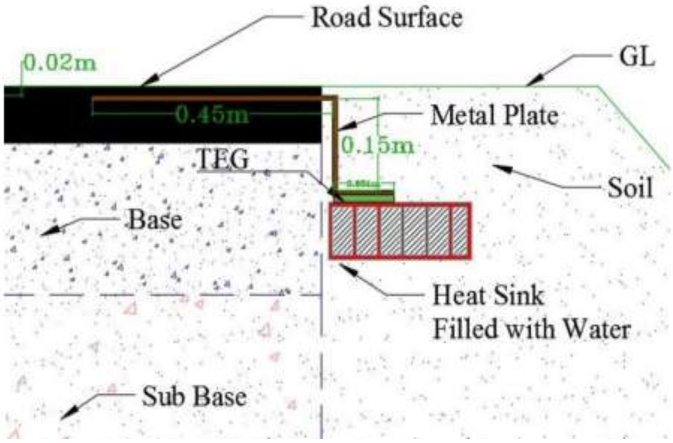


Fig. 8: Schematic of the thermoelectric energy harvesting prototype in pavement.

It was divided into three sections: a heat absorber at the edge, placed 20 millimetres below the surface of the pavement, a heat transporter buried at 180 mm beneath the surface of the nearby earth, a Heat Transfer Plate that transmits thermal energy into the TEG module's top. Two $0.5\ m \times 0.175\ m \times 0.0375\ m$ strips of asphalt pavement $450\ mm$ apart were removed at the edge of the asphalt pavement roadway to insert the energy harvester. The prototype was installed, and a $900\ mm\ x\ 450\ mm\ x\ 450\ mm$ pit was constructed in the ground along the road to make room for the data-gathering device. Both the negative and positive poles of the TEGs were extended to the ground and connected in series. When measuring the output voltage V and current I, an external resistance of 8.3Ω is used. They showed that 2 TEGs' average thermal output gradient ranges from 6.5 to 7.5 degrees Celsius. For the prototype with 2 TEGs, the output power produced ranged from $5\ mW$ to $16\ mW$, while the average output voltage was between 520 mV and 650 mV, and the output current was between 10 mA and 18 mA. For the prototype with 4 TEGs, The output voltage and current ranged from $320\ mV$ to $410\ mV$ on average and 11 mA to 16 mA, respectively. The final power output that was produced ranged from 4 to 6.5 milliwatts. The output voltage and current for both prototypes ranged from 500 mV to 700 mV and 22 mA to 25 mA, respectively. As a result, the output power that was produced was between 11 and $22\ mW$.

Using the temperature variation theory of thermoelectric technology, the work in [16] designed the Road Thermoelectric Generator System (RTEGS). They selected heat-transfer-capable vapour chambers and positioned them $20{-}30\ mm$ below the surface of the pavement, with one end of the chamber embedded in the pavement, and the other end exposed to the roadside and bonded to the hot side of TEG as shown in Figure 9. They performed an indoor and outdoor test, for indoor test, slab samples were heated using a $500\ W$ iodine-tungsten lamp, which was utilised to replicate sun radiation. During the test, the water's temperature in the tank was monitored using PT100 temperature sensors, and the slab surface temperature was recorded every ten minutes using an infrared thermal imaging camera. The maximum output voltage was recorded at $0.737\ V$, during the first stage of slab cooling, when the temperature differential among the slab surface and the water in the tank was $34.7\ °C$. The slabs were set up in an open space with direct sunshine for the outdoor test. The data collection technique was the same as for indoor testing, and at a temperature differential of $15\ °C$ between the water in the tank and the slab surface, the output voltage peaked at around $0.41\ V$.

The work in [17] carried out a field testing of the road thermoelectric generator system subject to a complete seasonal shift. The model for the asphalt pavement in their experiment was a two-stack slab sample that was $300\ mm$ by $300\ mm$ and $100\ mm$ thick.

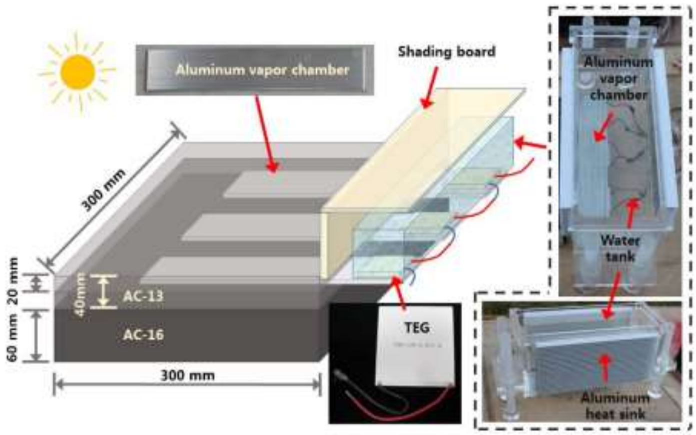


Fig. 9: Illustration of the RTEGS

Fig. 10: Organic glass water tank prototype

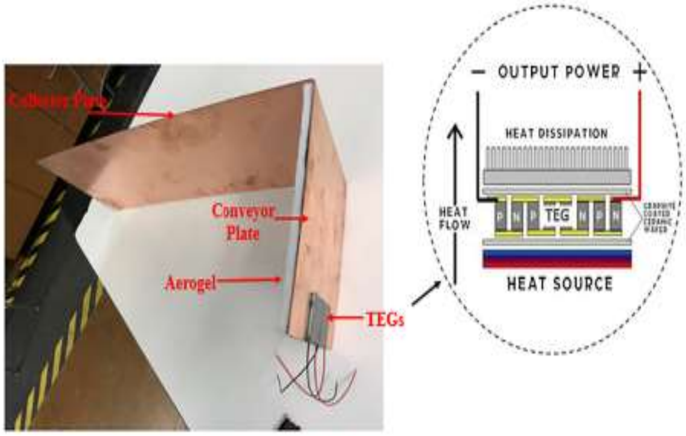


Fig. 11: TEG with heat collection plate

The experiment had an aluminum vapour chamber measured 3mm in thickness, 300mm in length, and 60mm in width. To reduce the cold side temperature of the TEG, an organic glass water tank was installed as seen in Figure 10. The testing was the same as the one used by [16], the output peak voltage was recorded at $0.564\ V$. After about 8 hours, the voltage output exceeded $0.3\ V$. The output peak voltage was recorded as $0.275\ V$.

The authors in [18] created a cutting-edge thermoelectric generator system, with an L-shaped copper plate of $0.15\ cm$ thickness made up of two parts: an $18\ cm$ long vertical heat conductor to transfer heat to the lower pavement layers, and a $50\ cm$ long heat receiver to collect heat from the pavement as seen in Figure 11.

In the laboratory, $60\ mm$ thick asphalt mix slabs were created, and $30\ mm$ deep copper plates were inserted to transport and collect pavement heat. The soil-filled bucket has a heat sink and insulating box implanted in it as depicted in Figure 12. The temperature of the asphalt surface was adjusted between $55 - 62\ °C$. During their field test, the energy-collecting device produced an average power output of $29\ mW$.

Thermoelectric generator (TEG) modules were used in a study in [19] on energy harvesting from road pavements, two distinct types of cement and asphalt pavements were designed and built inside a $150\ x\ 150\ mm$ square box that stood $50\ mm$ tall. Two sets of TEGs were placed for each road pavement, as seen in Figure 13.

The surfaces that were heated were fixed to the pavement's underside, while the surfaces that were cooled were fixed to heat sinks, one of which was submerged in water and the other of which was exposed to ambient airflow.

The asphalt pavement's maximum temperature was around $53.6\ °C$, whereas the cement's maximum temperature was approximately $47.6\ °C$. The electromotive force (e.m.f.) values for both asphalt and cement were strongly associated with the temperature differential, especially for water cooling. The maximum e.m.f. in natural airflow for the asphalt and cement pavements was $77.6\ mV$ and $49.6\ mV$, respectively. Nevertheless, the highest e.m.f. in water cooling for cement and asphalt was $134.4\ mV$ and $168.5\ mV$, respectively. The Table 4 below summarizes thermoelectric energy harvester technologies, their collector plates and power output.

Fig. 12: Field installation and data collection

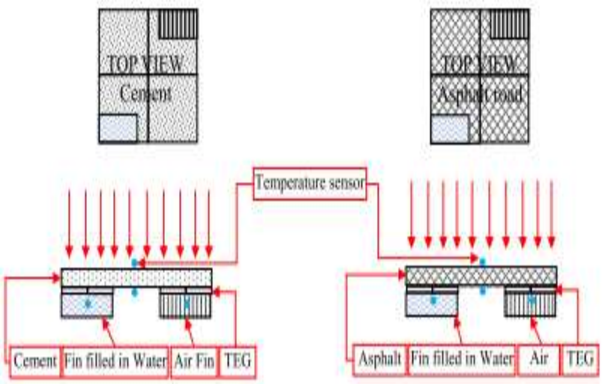


Fig. 13: The schematic of cement and asphalt road pavement

Table 4 Summary of Thermoelectric Energy Harvesting Technologies, their collector plates and power output

Research	Collector Plate	Pavement size	Pavement type	Type of testing	Power output
[15]	Z-shape copper plate	$0.5m \times 0.175m \times 0.0375m$	Asphalt	In-field test	600mV
[16]	I-shape aluminium plate	$0.3\ m \times 0.3\ m \times 0.1\ m$	Asphalt (SBS, AC-13 and 20)	In-field and Lab test	$275\ mV$
[18]	L-shaped copper plate	$0.5\ m\ \times\ 0.2\ m$	Asphalt	In-field test	29mW
[19]	Pavement generator mechanism	$0.15\ m \times 0.15\ m \times 0.05\ m$	Cement and Asphalt	In-field test	$134.4\ mV$ and $168.5\ mV$

C. Piezoelectric Energy Harvesting Techniques

Millions of moving cars on the road constantly put stress, strain, deformation, and vibration on it. There is an increased chance of pavement damage since these energies are squandered as thermal energy and dissipate in the pavement. To capture such mechanical energy, researchers have looked for novel methods. There is a possibility of transforming these stresses and vibrations into energy; piezoelectric technology has the most potential to do this. The authors in [20] presented a review with a focus on piezoelectric devices, the review paper examines the social and environmental impacts of road energy harvesting technologies while highlighting the state-of-the-art in this field. The article offered a thorough analysis of systems for harvesting energy from roads. According to the literature they studied, it is possible to expand highway energy harvesting technology to a large, practical scale, but this would require careful consideration from several perspectives.

1) Piezoelectric Prototype Designs

The authors in [21], assessed the application performance of two methods for creating stacked piezoelectric energy-harvesting units in terms of structural strength and electromechanical conversion performance. Their study also promised to determine the best method for producing the units. They utilised a U-shaped interlayer copper foil electrode configuration to improve the quality and efficiency of wire welding by successfully preventing interlayer charge breakdown. The copper foil that was positioned between the pieces and the top and lower silver electrodes of each piezoelectric ceramic component were electrically connected using conductive silver paint glue. Each piece of copper foil featured a U-shaped pin on one end, which served as the interlayer copper foil's external electrode when it was welded to the wire as depicted in Figure 14.

The output currents and output power of the stacked piezoelectric energy-harvesting units under optimal load are 2.08 mA and 2.12 mA for the interlayer copper foil electrode and 89.89 mW and 86.53 mW for the lateral lead electrode, respectively. The findings show that the parallel linked units made using the multilayer adhesive technique can raise the output power by 22.80 mW and the terminal voltage by 28.0 V at 0.7 $MPa-$ 10 Hz.

In a paper by [22], the authors assembled piezoelectric units, full bridge rectifiers, and package structures to create a piezoelectric transducer that was suitable for road traffic. It resembled a box and was 30 $cm\ by$ 30 $cm\ by$ 6.8 cm. The piezoelectric transducer's nine piezoelectric units make up its essential parts. Three piezoelectric ceramics of the PZT-5H material type, are placed in parallel with each piezoelectric unit as seen in Figures 15a and 15b.

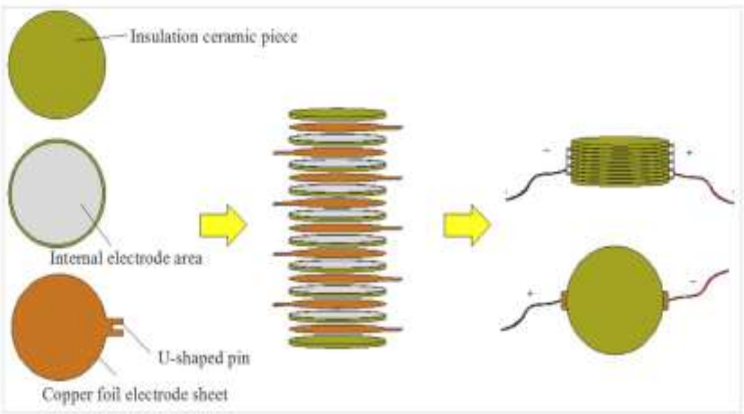
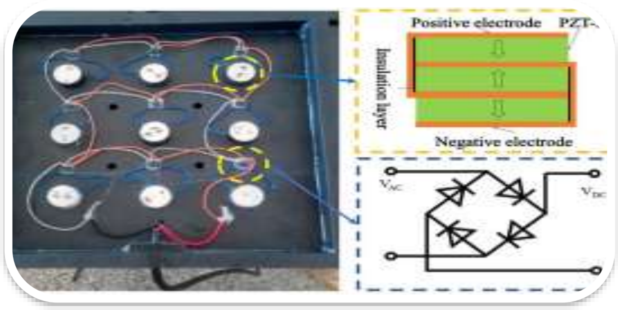


Fig. 14: The interlayer copper foil electrode configuration in the form of a U



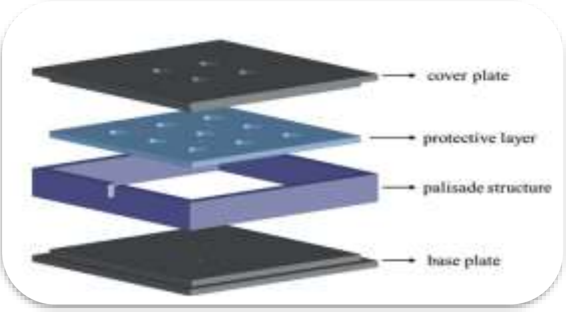


Fig. 15a: Piezoelectric transducer structure
structure

Fig. 15b: Piezoelectric transducer Prototype

Figure 16. Piezoelectric transducer Installation

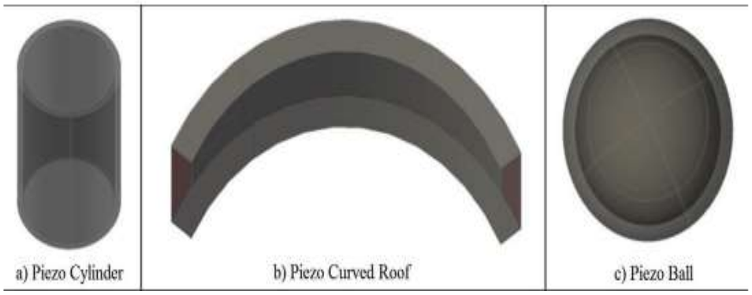
The dimensions of the indoor test road were 280 $cm \times 90\ cm \times 24\ cm$. Underneath the pavement was a cushion made of macadam stabilised with cement as displayed in Figure 16. With an execution frequency of 3,600 times an hour and 100,000 times overall, the wheel force on was set to 2.6 kN.

Throughout the loading operation, there was a 8.9% difference between the lowest and greatest open circuit voltages of 173.8 V and 190.8 V, respectively. They indicated there was a greater likelihood that the vehicle's back tyre would completely act on the transducer, producing a bigger voltage.

In a study by the authors in [23], they suggested several bulk piezoelectric element shapes, such as piezo cylinder, piezo curved roofs, and piezo balls, to be placed inside the piezoelectric layer. Piezoelectric components of the first structure, the piezo cylinder, are used to produce and test PZ-EHPS specimens in the lab in order to verify corresponding FEMs. All 3 PZT elements they design are shown in Figures 17a, 17b and 17c.

The outcomes of the simulations of the electric potentials generated in the specimens under stress are shown in Figure 18. It can be seen that when the paris filler plaster is removed, the electrical potential difference between Nodes 1 and 2 at 1 Hz with a 133 N load increases from 0.9 V to 10.14 V. On the other hand, the specimen without an insulative filler experiences a drop in voltage output from 10.14 V to 6.72 V when the load is reduced from 133 N to 88 N.

The authors in [24], used a group of piezoelectric transducers to build a compression-based pavement energy collecting system. They also investigated component material selection in relation to four technical device criteria. Figure 19 shows the structure of the prototype, its primary parts are the transducer and its carrier substrate, protective pad, rigid bearing shell, and other parts.


a) Piezo Cylinder
b) Piezo Curved Roof
c) Piezo Ball

Figures 17a, 17b and 17c. PZT elements in the piezoelectric layer

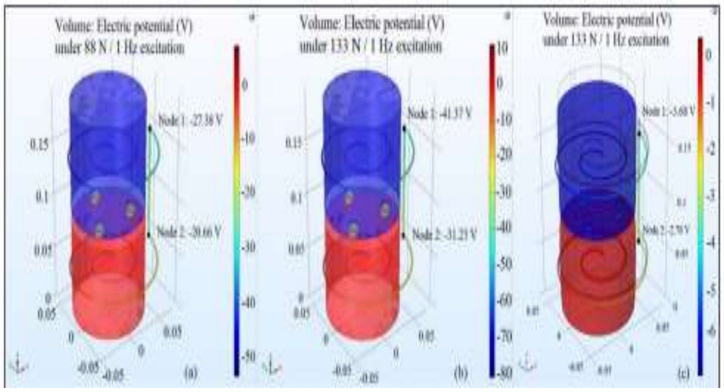


Fig. 18: Potential electric in PZ-EHPS specimens: under 88 N load without insulating filler[a], with 133 N load without insulating filler[b], and under 133 N load with plaster of paris filling[c]

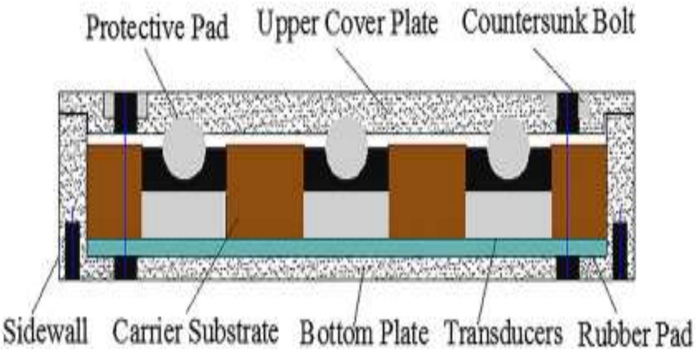
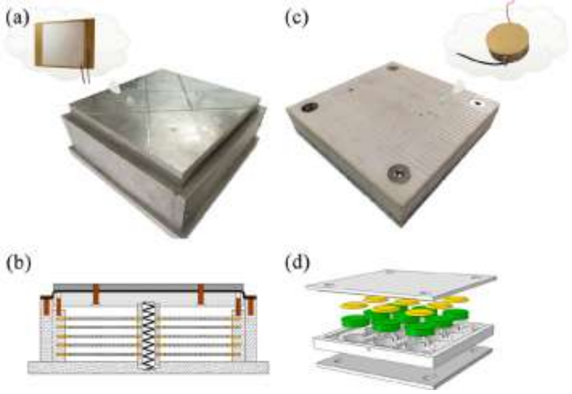


Fig. 19: Schematic diagram of the prototype structure

They explained that in order to optimise the amount of energy collected from tyres' dynamic loading, the device should be positioned between two-wheel paths, each with a width of 0.5 m. The simulation tests include a load range of $0.2\,MPa$ to $0.7\,MPa$. The electric energy output effect of several transducer connection choices was explored by applying a typical axle load through the MTS Landmark (MTS810) and measuring the transducer voltage outputs at different frequencies, as well as in series and parallel connections. Using the mechanic-electric response as a basis, the device component configuration is determined. This configuration entails a revised upper cover plate made of polypropylene, a rubber pad measuring $1\,mm$, a protective pad in the form of a ball, and a piezoelectric transducer with eight layers stacked on top of one another.

The results they got from the MTS loading test show that a parallel connection produces more consistent and efficient electricity output. The number of transducers, traffic loading, and frequency all positively correlate with power outputs. With a $4\,k\Omega$ loading, the $150\,mm \times 150\,mm$ device can produce a maximum power output of $50.41\,mW$. The device maximises energy harvests with nine parallel transducers.

In an article by the authors in [25], an energy promotion system appropriate for road piezoelectric micro-energy features is presented. In the study, they modelled a $160\,mm \times 160\,mm$ stainless steel cantilever device that has internal energy harvesters composed of PZT-5H piezoelectric material and a bronze base as depicted in Figures 20a, 20b, 20c and 20d. Also, a PP-based stacked device of $150\,mm \times 150\,mm$, with PZT-5H piezoelectric material used for its internal stacked energy harvesters as displayed in Figures 20a, 20b, 20c and 20d.



Figs. 20a, 20b, 20c and 20d: Showing a schematic and pictures of the stacked and cantilever device configuration

The authors applied a $0.7\,MPa$ vehicle standard load using MTS. They stated that the frequency of vibration that the object being crushed by the car produces is usually low, ranging from $3\,Hz$ to $12\,Hz$. As a result, the device's electrical signal possesses instantaneous and low-frequency characteristics when driving in actual intermittent traffic.

Still in the work by [25], the authors explained that the prototype demonstrated strong electrical responsiveness under a range of loading conditions, and both the energy promotion systems and the original stacking device's open voltages have somewhat risen. Under the circumstances of $0.3\,MPa – 10\,Hz$, the output voltage of the Type-1 and Type-2 systems is $24\,V$ and $44\,V$, respectively, whereas the output voltage of the primary prototype was $15.8\,V$. In comparison to the initial device, there is a roughly 52% and 178% increase in output voltages, respectively. They concluded that the Type-2 system's output power, which is 93% more than the Type-1 system's, reached $208\,mW$.

For use in highway applications, [26] presents a polyvinylidene fluoride (PVDF)-based piezoelectric energy harvesting module. The schematic and image of unit harvesters are shown in Figure 21.

The module's dimensions ($15\ cm\ x\ 15\ cm$) are chosen to allow the tyre to pass by and press a sizable portion of the surface consistently. An evaluation of the integrated harvester module, which is displayed in Figure 22, is conducted using a model mobile load system (MMLS3). They discovered that the module could deliver an instantaneous power output of up to $200\ mW$ across a $40\ k\Omega$ resistor at a speed of $8\ km/h$ and $250\ kgf$.

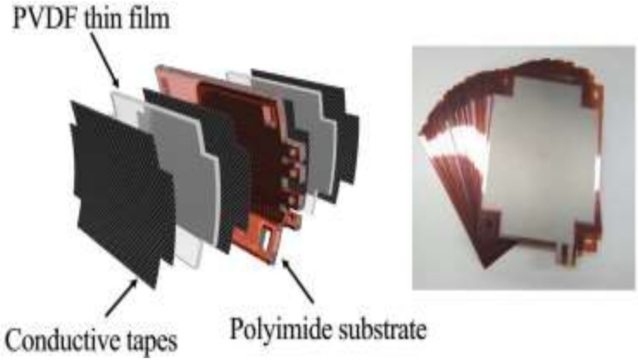


Fig. 21: Schematic and image of the bi-morph structure energy harvester

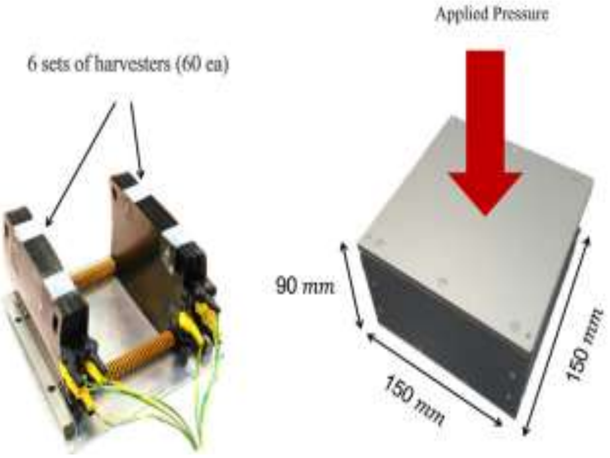


Fig. 22: The interior and exterior of a constructed energy harvester module, with stacked energy harvesters inside

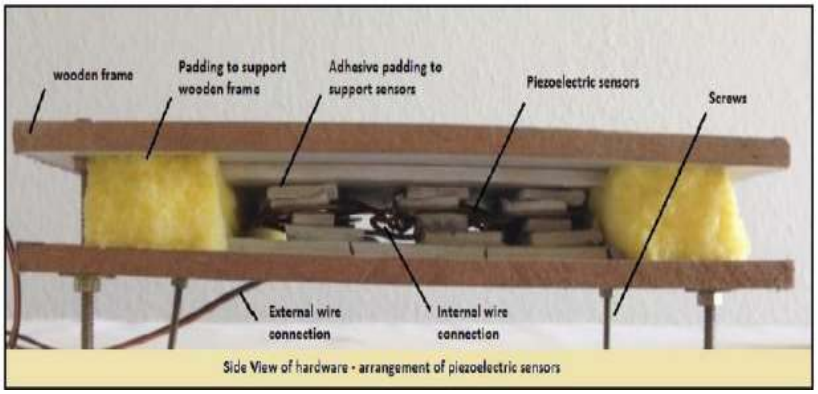


Fig. 23: A labelled side view of the suggested prototype

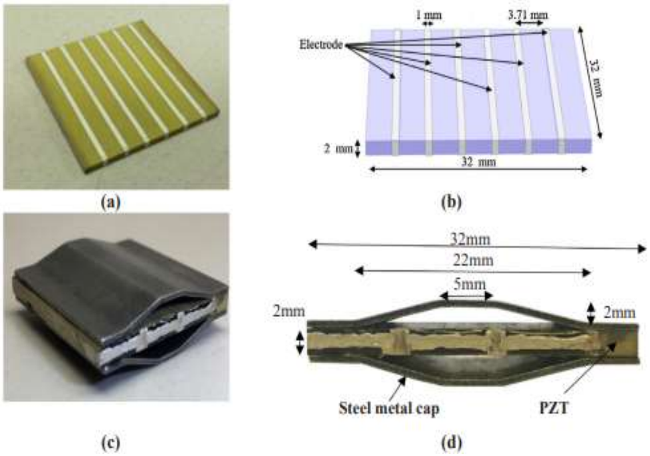
The module's dimensions (15 $cm\ x$ 15 cm) are chosen to allow the tyre to pass by and press a sizable portion of the surface consistently. An evaluation of the integrated harvester module, which is displayed in Figure 22, is conducted using a model mobile load system (MMLS3). They discovered that the module could deliver an instantaneous power output of up to 200 mW across a 40 $k\Omega$ resistor at a speed of 8 km/h and 250 kgf.

A vibration-sourced piezoelectric energy harvester is proposed by [27], and the simulation outcomes from COMSOL Multiphysics serve to validate them. Additionally, they created a hardware module prototype for piezoelectric energy harvesting as shown in Figure 23. The highest output power of their suggested piezoelectric energy harvester is 57 mW, whereas the average power consumption of a data transmitter in these systems is 120 mW. Additionally, power outputs of around 95 mW and 220 mW, respectively, were produced by the various load resistance and acceleration levels.

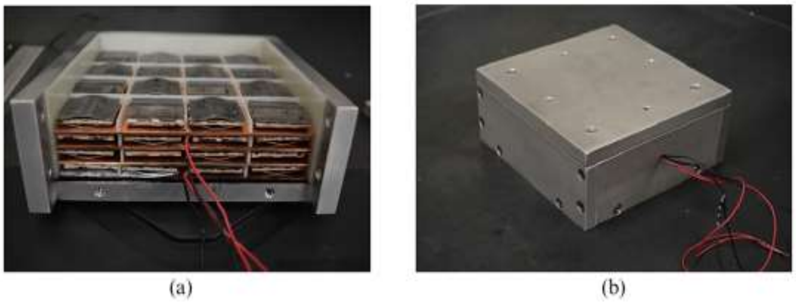
The work in [28] suggested a displacement-amplifying mechanism-equipped bending-type piezoelectric energy harvester for smart roads. The dimensions of the proposed harvester were measured and developed to be 120 $mm\ by$ 60 $mm\ by$ 70 mm. The harvester frame was equipped with four springs, each measuring 10 mm in diameter and 15 mm in height, at each of its four corners. During the test, the weights were 5.7 kg, 9.8 kg, 15.2 kg, and 21.9 kg, and at intervals of 0.5 mm, the displacements were adjusted from 1 mm to 2.5 mm. The maximum output power was recorded at 130 $k\Omega$ for all input displacement instances. In every scenario, the highest possible output power was 3.93 mW, while the highest possible output voltage was 22.63 V.

The work in [29] suggested conducting research on the viability and promising future of road energy collecting using piezoelectric technology. Additionally, they conduct a PZT-generating capacity test using the PZT-4/8/5H layer-to-layer building method. This involves connecting four PZT material pieces in parallel, each with an inner diameter of 15 mm, an outer diameter of 45 mm, and a thickness of 5 mm. At a load condition of $300N$ and 10 Hz, the peak voltage of the PZT-4, PZT-8 and PZT-5H are 14.9 V, 14.5 V and 22 V, respectively. At $1000N$ and 10 Hz the peak voltage of the PZT-4, PZT-8 and PZT-5H are 48 V, 45 V and 70 V, respectively. They observed that, while operating in the d-33 mode, PZT-5H, on the other hand, generates more power per unit volume and is more appropriate for piezoelectric energy harvesting.

In the work in [30], the authors conducted a forensic investigation to look at piezoelectric transducers' fatigue failure after repeated stress. A unique bridge transducer design with multilayer poling and electrode arrangement was developed because of their effort. A square-plate ceramic PZT-5X measuring 32 mm on each side and 2 mm in thickness was electroded using silver paste. With an electrode width of roughly 1 mm and an inter-electrode spacing of 3.71 mm, the electrodes split the ceramic into seven segments. After being heat-treated to improve hardness, annealed 4130 alloy steel sheets with a thickness of 0.6 mm were stamped to create the steel end caps as shown in Figures 24a, 24b, 24c and 24d.



Figs. 24a, 24b, 24c, 24d: PZT strip with electrodes and multilayer poling^{a}, PZT strip dimensions^{b}, Bridge transducer Fabrication^{c}, and geometrical Parameters^{d}.



Figs. 25a and 25b: Energy harvester with transducer arrays: (a) inside; (b) outside configurations.

(a) (b)

Fig. 26a and 26b. Arch transducer and the asphalt plate.

In a study by the authors in [32], to test the optimal energy harvester performance, a prototype made of two copper plates layered with piezoelectric discs was put together in between batches of asphalt. The components of the energy harvester were two polystyrene sheets, two copper plates with electric wire mountings, and piezoelectric discs.

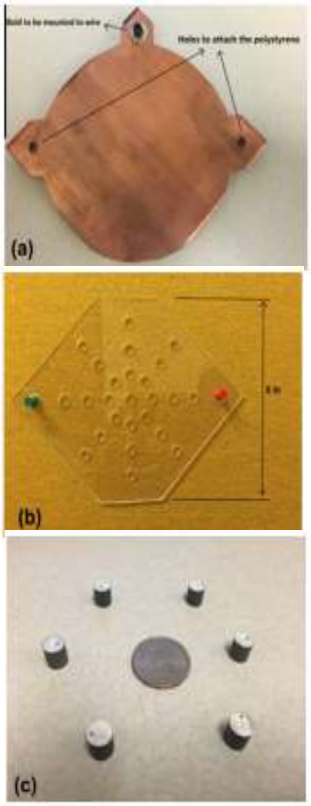


Fig. 27a: The copper plate with 152mm. diameter, **Fig. 27b.** the polystyrene sheet with pre-holes, **Figure 27c.** The piezoelectric disks (diameter of 8 mm and thickness of 8 mm).

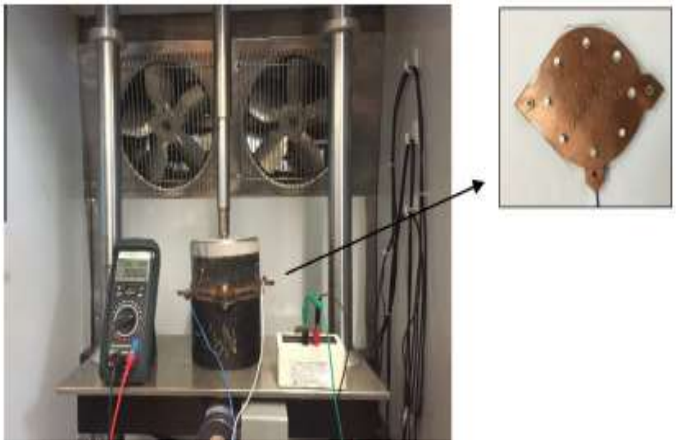


Fig. 28. The prototype of the final assembly housed in the hydraulic loading system

The diameter and thickness of these copper plates measure 152 mm and 6.35 mm, respectively as seen in Figures 27a, 27b and 27c. The mixes were compacted to 152 mm in diameter after being chopped to 38 mm and 127 mm in thickness for the top and bottom layers, respectively.
The setup of the laboratory is depicted in Figure 28 in which they concluded that when greater load values were used, the sensitivity was more noticeable between 4 °C and 22 °C. The prototype that had four piezoelectric disks was more temperature-sensitive. The maximum power of 3.7 mW was recorded on 3 kN load at 4 °C, while on 22 °C and 40 °C the power outputs were, 3.5 mW and 3.4 mW, respectively. Table 5 below shows a summary of piezoelectric energy harvesting technologies, their testing techniques and their respective power output.

Table 5 Summary of Piezoelectric Energy Harvested Technologies, their collector plates and power output

Research	Type of PZT	Testing techniques	Voltage/Power output
[21]	---	MTS test system	22.80W
[22]	PZT-5H	MMLS-1/3	182.3V
[23]	---	COMSOL Multiphysics	10.4V
[24]	---	MTS Landmark (MTS810)	50.41mW
[25]	PZT-5H	MTS Landmark	208mW
[26]	---	Mobile Load Monitoring System	200mW
[27]	PZT-5J	COMSOL Multiphysics	57mW
[28]	PZT-PZNM	Press Machine	3.93mW
[29]	PZT-4/8/5H	Press Machine (slide caliper)	70V
[30]	PZT-5X	COMSOL Multiphysics	28.7mW
[31]	PZT-5H	MMLS 3	202V
[32]	---	Universal Testing Machine	3.7mW

4. DISCUSSIONS

After analyzing all the articles, the various techniques have their unique ways of harvesting energy, but the thermoelectric technique is far more challenging, as it requires a temperature gradient between the top and bottom part of the road; this cannot occur effectively in a natural way [19]. So, in order to keep the temperatures low beneath, a coolant is needed which in most cases can be water. The authors [16] and [18] suggested that a heat sink would effectively keep the temperature low at the cool side of the TEG. According to [18] in which thermoelectric investigation was performed, finite element simulations demonstrated that the L-shaped plate with a 20 cm width performed better than the others at transmitting heat. Furthermore, their investigation revealed that the insulating box used as a thermal barrier was very functional.

However, [14] stated that the SHTE-AP they fabricated does not have enough power to generate electricity. They suggested that the maximum power point tracking method be used in conjunction with an AC/DC converter, that the system's configuration be optimized, and the pavement's thermal-electric properties be altered, while the TEGs' conversion efficiency can be raised in order to enhance power. The work in [16] emphasized that, in addition to reducing pavement defects brought on by high temperatures, RTEGS can lower road surface temperatures, which helps mitigate the urban heat island effect. However, it has been noted that more research is required to validate the idea of embedding vapour chambers in pavement structures without sacrificing the pavement's mechanical performance or durability.

In electromagnetic technology, the logic is all behind Faraday’s law and Joule’s law. This technology looks promising for energy harvesting on roads as most of the research especially in [10-12] proposed an Electromagnetic Speed Bump that will harvest energy lost from moving vehicles. They all indicated that this technology would help to increase road safety and reduce the number of accidents in many ways. They also mentioned that their prototypes need more study and investigation as they have gaps and loopholes, which may cause negative impacts in the long run. The authors in [9], pointed out that using plastic rubber for the upper plate doesn't alleviate stress and, in fact, increases concentrated stress at the connections. They also proposed that enhancing the prototype by including extra elements like a gearbox and amplifying rotations could considerably boost its output. However, this would make the prototype more complex and challenging to implement and maintain during actual usage.

According to [23] and [29], piezoelectric technology is more suitable for high vibration frequency which can be achieved at high speed, and they suggested that the piezoelectric is more suitable for roads with high-speed limits. There are different piezoelectric prototypes proposed by researchers i.e., a displacement-amplifying mechanism was used in the design and construction of a bending-type piezoelectric road energy harvester by the authors [26], and [28] in which they proposed flexible energy harvesters which are fabricated with polyvinylidene fluoride films. The works by the authors in [24] and [31] proposed different prototypes to harvest energy using piezoelectric technology and both works concluded and reported that there is a possibility of harvesting more than 50kW energy from their prototypes in a single lane. The piezoelectric energy harvesting system on pavement, according to [23], can be split up into smaller sections to increase the electric potential over each segment and decrease the amount of vehicle loads in each segment.

Additionally, they noted that the area within the range of the edge of each segment of energy-harvesting pavement is where the crucial electric potential occurs. According to [20], piezoelectric technology possesses an unquestionable benefit for encouraging the usage of hybrid and electric cars since it has zero greenhouse gas emissions. The works in [23] and [33] investigated and found that increasing the thickness of the piezoelectric layer can increase the energy harvested.

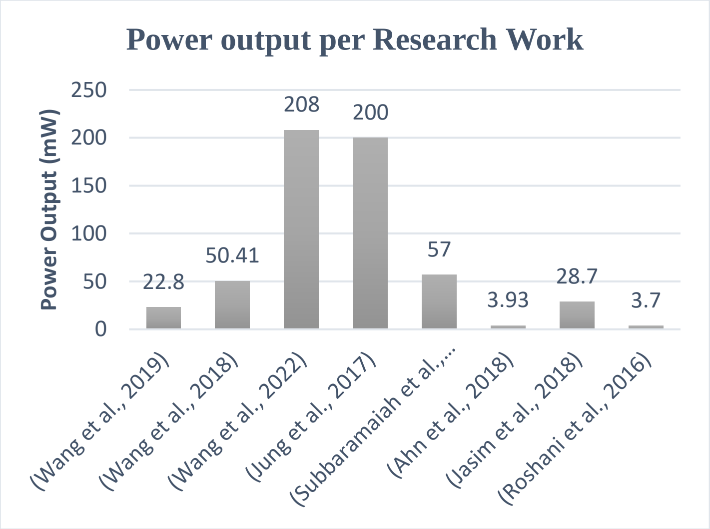


Fig. 29: Result detailing the power output (mW) per research

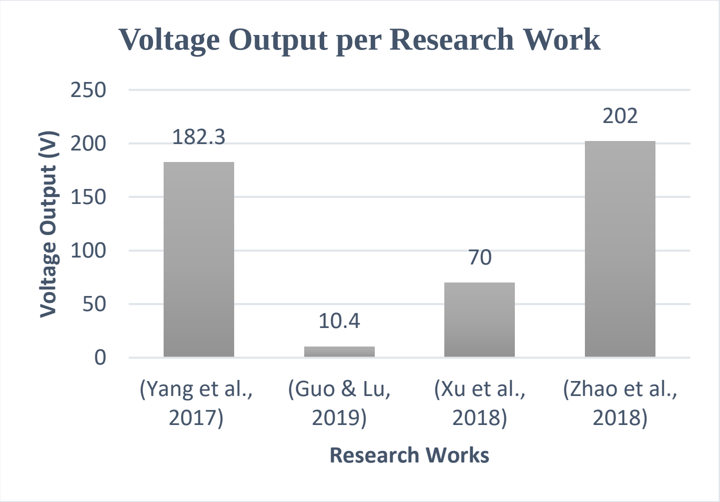


Fig. 30: Result detailing the voltage output (V) per research work

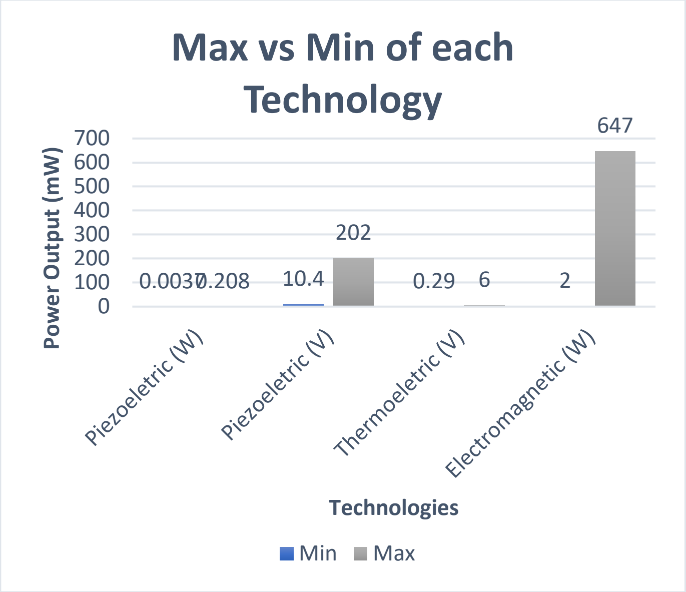


Fig. 31: Graph comparing the maximum and minimum output from each technology.

From our observations documented in the results in Figure 29 and Figure 30, we can notice the different power and voltage outputs produced by different works in the literature, respectively, with Wang et al., as in [25] producing more power and Zhao et al., as in [31] having to produce more voltage.

Life cycle studies of such energy-harvesting techniques are also required to evaluate the viability of energy-harvesting roads thoroughly. Most of these experiments on energy-collecting techniques are still in the laboratory demonstration stage, and most technologies would still be more expensive than using fossil fuels to generate electricity [34]. Hence, these techniques still need to be developed and prepared for real-world use. The electromagnetic energy harvesting technology performs at least 15 W better on average than the other strategies [8]. The road's deformation and vibrations can be used by piezoelectric technology to collect energy. However, vibration-based mechanical energy generation presents difficulties because of variations in vehicle speed and stress intensity. These technologies become more difficult to use because of their low durability from mechanical shock, temperature variations, humidity, and dust. For this reason, durability and safety must also be the focus of future research.

The results obtained in Figure 31 can also be used to deduce the output difference between the three technologies focus; it is worth noting that the highest power output of the electromagnetic technology was obtained during an in-field experiment.

According to the studies that were reviewed in this work, it is evidently clear that there is energy to be harvested, just that there is a need for more implemented prototypes, which may give better power outputs since most of the outputs obtained were performed during a lab test.

5. SUMMARY AND CONCLUSION

This work presents an analysis and systematic literature review of energy harvesting from road projects, with a specific focus on Electromagnetic, Thermoelectric, and Piezoelectric technologies, revealing promising prospects for harnessing energy from road infrastructure. These methods show potential for sustainable energy generation, with each technology having its unique advantages and challenges.

Many techniques, i.e., Electromagnetic, Photovoltaic, Piezoelectric, Geothermal, Thermoelectric, etc., were introduced by different researchers, and all those techniques were reviewed and analyzed by other researchers in the past and in ongoing studies. This analysis and systematic literature review focused on three types of road energy harvesting technologies: piezoelectric, electromagnetic, and thermoelectric. All the findings from the studies were encouraging, and several strategies have been suggested to try and lessen the various difficulties that each technique encounters. But before these methods can be used widely and profitably, many issues still need to be resolved.

The technology is more interesting in terms of Piezoelectric harvesting technology, and many studies focused on testing the performance of PZT-5H using the UTM. The authors in [32] mentioned that by increasing the frequency in their prototype, the generated power increases, and the loading duration on the piezoelectric discs is minimized; however, they did not specify which PZT material was used in their research. The authors in [31] used a different technique by employing an MMLS3 machine to test their prototype, and they used an Arch transducer. When they studied the asphalt plate after installing the prototype, they discovered a 6 mm-deep rut had formed in the centre of it. This provides some insight into the potential effects this technology, if applied at this point, could have on the roads. Thermoelectric technology depends too much on the temperature of the environment, which is hard to control, this has been the main challenge for this technology. In the work by authors in [16], their prototype installed a water tank at the cold side of TEG to maintain a stable temperature difference, as they also mentioned that to validate the idea of integrating vapour chambers into pavement structure without sacrificing its durability and mechanical performance, more research is required. In the work by the authors in [19], the water-cooling technology used proved to be more efficient than open airflow. Their study showed that heat could be conducted from the top to the bottom surface of a 50 mm thick pavement without needing metal as a heat conductor. The work in [18] ran a Finite Element simulation, which showed that the 20 cm L-shaped collector plate they used in their prototype performs better heat transfer than other configurations.

Upon examining the three focused methods of road energy harvesting, it is evident that further development of these technologies can result in low-cost, efficient, eco-friendly energy-producing systems that are easy to incorporate into the infrastructure. Though most studies are currently conducted in lab configurations to test the technologies to their limits and see how they will affect pavements after installation. Researchers have shared their ideas and suggestions on how these technologies will help in roads and how they will be implemented. Piezoelectric is more sophisticated and integrating it into the pavement of roads can cause some negative impacts. The lifespan of these PZT materials under constant pressure and vibrations is still unknown, and maintenance after an accident will also cost much. For future research on Piezoelectric techniques, researchers should focus more on the type of PTZ that possesses more durability properties and test them under different areas with different climates.

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