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FLOOR TILE ENERGY HARVESTER: DESIGN STRATEGIES, PRODUCT DEVELOPMENT AND PERFORMANCE ANALYSIS

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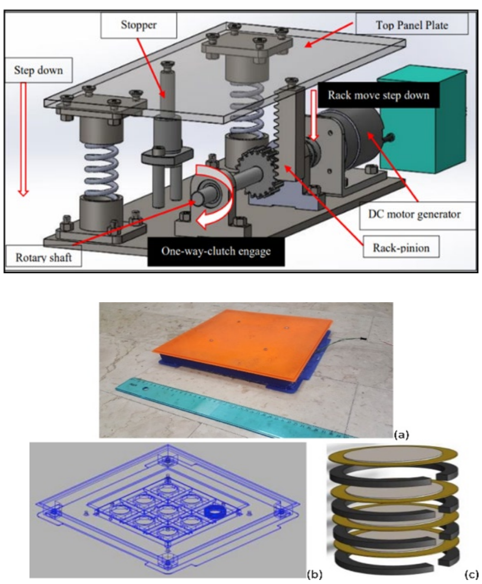
Graphical abstract



Abstract

Developing nations face formidable challenges in the realm of energy generation. Leveraging renewable energy resources emerges as a strategic solution to address this energy crisis. Footstep energy conversion, although a technology in its nascent stage in certain developing regions, holds great promise for electricity generation. This comprehensive review delves into the intricate analyses of the underlying mechanisms for energy extraction, specific design considerations, advancements in prototypes, ongoing implementation initiatives, and the economic dimensions associated with various footstep energy harvesting technologies. The structure of footstep power generation proves to be an economical and reasonable energy solution for individuals in common settings. Its applicability spans numerous uses in rural areas where power availability is scarce or entirely absent. By harnessing energy from non-renewable sources, footstep power generation becomes invaluable for locations without conventional power infrastructure. Its efficacy extends to all roads and various footstep applications, contributing significantly to the generation of unconventional energy such as electricity. 19 journals have been reviewed in terms of design, product development, and performance analysis.

Keywords: Renewable energy, harnessing energy, energy generation, leveraging renewable energy, and footstep power generation.

1.0 INTRODUCTION

In numerous rural areas, an enduring lack of electrical power poses a recurrent challenge that hampers progress and development. These regions frequently encounter difficulties in obtaining and sustaining a consistent electricity supply due to diverse factors, including insufficient infrastructure, geographical remoteness, and economic constraints. This power shortage not only affects the daily lives of rural residents but also acts as a significant obstacle to socioeconomic advancement. Within these underserved rural communities, the electricity deficit gives rise to a range of problems. It restricts access to vital services such as healthcare, education, and communication, creating obstacles for residents in accessing modern conveniences and opportunities [1].

Addressing this electricity shortfall in rural areas is imperative for achieving fair development and elevating the quality of life for the inhabitants. Extensive research has been conducted on the advancement of renewable energy harvesting systems (REHS) with the aim of harnessing energy from the surrounding environment. The primary objective is to establish a sustainable off-grid power supply for low-power applications. Furthermore, the electric energy generated by these systems can be effectively utilized to power low-energy electric devices, including LED billboards, safety indicator lights, and environmental monitors [2,3].In the pursuit of harnessing energy from the subcutaneous environment, diverse approaches have been explored, encompassing photovoltaic [4–7] thermoelectric [8–11] thermoelectric generators [12–15], piezoelectric [16–21], electromagnetic transducer [22–24], triboelectric effects [25–27] and various hybrid energy harvesting techniques [28–30]. Each of these technologies is currently positioned at different stages of development, exhibiting its own set of unique advantages and drawbacks.

This paper focuses on examining the green energy prototype design of floor tiles within the field of kinetic energy harvesting and delves into various ambient energy sources, including solar power, which falls within the broader category of energy conversion. This area has garnered significant attention in the realm of renewable energy generation, encompassing a range of technologies aimed at capturing energy from motion-based sources such as vibrations, mechanical oscillations, and human movement to generate electricity. The fundamental principle underlying kinetic energy harvesting involves the use of transducers or energy harvesting devices capable of efficiently capturing and converting mechanical motion into electrical energy. Researchers have extensively explored the concept of extracting energy from footsteps. In this specific application, three main sources of energy are commonly utilized: piezoelectric, electromagnetic power, and photovoltaic.

2.0 OBJECTIVE

The aim of this paper is to present a critical review of the various technologies available for harvesting energy from roadway pavements in order to evaluate the applicability of these energy harvesting processes. The specific objectives are to:

- Describe about various mechanical design of the
- footstep energy harvesting technologies.
- Explore about footstep energy harvester design and prototype.
- Power output of the footstep energy harvester to harvest energy.
- Implementation effort and economic consideration.
- Design of the electric circuit for energy collection

3.0 PRINCIPLE OF FOOTSTEP ENERGY HARVESTING

3.1 Electromagnetic Generator

Faraday's principle, as elucidated in Eom (2013) [31], posits that an electric current is induced through the relative motion between an electric conductor and a magnetic field. The amount of electricity generated hinges on variables such as the speed of this relative movement, the strength of the magnetic field, and the number of coils involved [32]. In practical terms, the mechanical energy from a moving vehicle applies force or displacement to a mechanical system, creating the necessary relative motion between a magnet and a coil, thereby generating electrical power.

Beyond that, the electromagnetic working principle is grounded in the fundamental relationship between electricity and magnetism as outlined in Maxwell's equations. These principles serve as the foundation for the operation of diverse devices, including electric motors, generators, transformers, and various electronic components. When an electric current flows through a conductor, such as a wire, it produces a magnetic field around it. Conversely, when a magnetic field changes around a conductor, it induces an electromotive force (EMF) or voltage in the conductor. This phenomenon, known as electromagnetic induction, is pivotal in understanding the operation of electrical systems [2].

The basic principle of the footstep energy harvester system involves the utilization of an electromagnetic generator or motor generator, as explained briefly in the section below. This energy is harnessed by compressing linear springs, storing potential energy in the process. Later, the stored potential energy is converted into electrical energy through the rotation of a shaft connected to a generator. To enhance the rotational speed of this shaft, a set of bevel gears is employed. The generated electricity is then stored in a battery, subsequently converted from direct current (DC) to alternating current (AC) using an inverter. Furthermore, the system is designed to return to its original configuration through the use of a one-way clutch and additional springs. The operational concept of the proposed footstep energy harvester system is elucidated in a block diagram, as illustrated in Figure 1 [33].

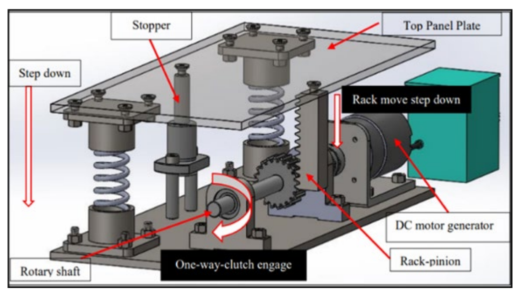


Figure 1 Principle of Electromagnetic Generator [34]

3.2 Piezoelectric Transducer

The piezoelectric effect, which involves specific materials generating electrical potential in response to mechanical strain or stress, has emerged as a central focus of research and innovation in the realm of energy harvesting. This phenomenon allows for the conversion of mechanical energy, resulting from the application of force or deformation, into a practical electrical form as shown in Figure 2. The exploration of piezoelectric energy harvesting holds significant promise and has attracted considerable attention in recent years, particularly within the context of sustainable energy generation [16].

Natural instances of the piezoelectric effect are evident in certain materials like Rochelle salt, cane sugar, bone, and quartz. However, modern piezoelectric devices predominantly employ specially synthesized materials that exhibit an enhance piezoelectric effect. The following sections will delve into the fundamental principles underpinning the direct and converse piezoelectric effects, examining their applications and significance in the development of efficient piezoelectric devices [35,36].

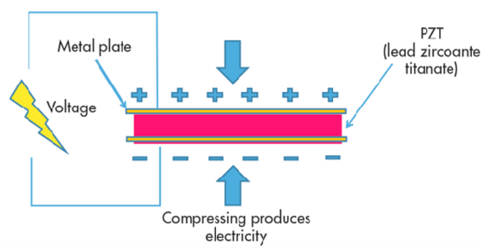


Figure 2 Mechanism of Piezoelectric system [37]

3.3 Photovoltaic Power Generation

A photovoltaic (PV) system, commonly known as a solar power system, transforms sunlight into electricity utilizing solar cells. When sunlight interacts with the solar panels, it stimulates electrons in the semiconductor material through a process known as the photovoltaic effect. This stimulation prompts the movement of electrons, generating an electric current. The direct current (DC) produced by the solar panels is then directed to an inverter, whose primary role is to convert the DC electricity into alternating current (AC). The converted AC electricity is subsequently supplied to the building's electrical panel, where it can be utilized to power electrical appliances, lights, and other devices, refer to Figure 3 [38,39].

The concept of "PV pavement," introduced in 2009, has spurred rapid research development over the years. Photovoltaic power generation relies on solar cells capturing solar radiation and converting it into electricity through the photoelectric effect. Despite challenges in optimizing PV pavement technology, it proves to be an environmentally friendly and renewable energy system capable of satisfying the electricity needs of the road system, holding substantial potential for the development of intelligent traffic systems. Future scenarios encompass applications such as replacing road markings, serving as a snow and ice melting system, guiding autonomous driving, and functioning as a charger for moving vehicles [40][41].

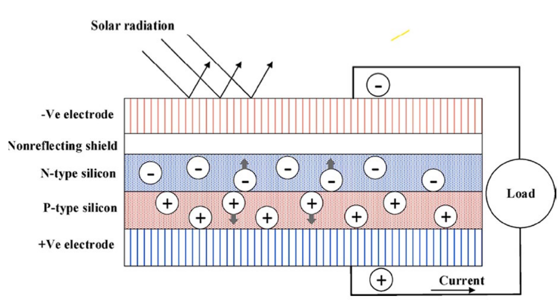


Figure 3 Photovoltaic power generation [41]

4.0 TECHNOLOGIES AND DESIGN OF FOOTSTEP ENERGY HARVESTED (FEH)

In this dedicated section that delves into the design of floor tiles based on findings from the preceding study, the emphasis is placed on the comprehensive design aspects of the floor tiles. This encompasses the integration of various energy harvesting technologies, including but not limited to piezoelectric, electromagnetic, and photovoltaic energy harvesters. The design considerations involve a thorough exploration of how these technologies can be seamlessly incorporated into the floor tiles to optimize energy harvesting efficiency and overall performance.

4.1 Design of Footstep Harvesting Using Piezoelectric

Cascetta et al. (2018) [42] proposed tile incorporates Lead Zirconate Titanate as its piezoelectric material. The conversion of input mechanical energy into electrical energy is achieved through a configuration of nine stacks positioned beneath the tile's upper surface. Each stack comprises five piezoelectric diaphragms (buzzers) separated by rings to facilitate vibration, as depicted in the Figure 4(a). Each buzzer, specifically a Piezotite 7BB-35-3L0, is linked to a full-bridge rectifier. Evans et al. (2019) [43] introduced piezoelectric stack energy harvesters involved the assembly of two aluminium plates, each measuring 600 × 300 × 10 mm. Support for the platform was provided by four force amplification frames, all constructed from steel and adhering to the specifications outlined in Figure 4(b). These frames were designed with a load rating of 1000 N and a force amplification factor of 7.1. The piezoelectric stack, a crucial component of the platform, was composed of 98 individual layers, each with a thickness of 0.5 mm. The arrangement involved connecting these layers in parallel to enhance the overall efficiency of the piezoelectric stack. The ensuing sections will delve into a detailed analysis of the platform's structural components and their implications for its performance. Abadi et al. (2018) [44] study presents the design and implementation of a tile incorporating piezoelectric transducers, specifically Lead Zirconate Titanate, to generate electrical pulses and harness energy from human footsteps. The tile comprises 20 parallel-connected piezoelectric transducers in the energy harvesting system. Selim et al. (2023) [45] study employed ceramic circular piezoelectric elements for energy harvesting, utilizing fourteen elements electrically connected in parallel to optimize power generation. The distribution of these piezoelectric harvesters across a rectangular floor tile allows for the capture of pressure energy from human footsteps. Additionally, a voltage doubler circuit, incorporating 1N60P Schottky diodes and 2.2 µF capacitors, was implemented to enhance electrical output. Kim et al. (2018) [46] designed a system utilizing a wireless foot switch as a piezoelectric energy harvester. An optimized PZN0.5C thick film cantilever-type harvester in supplying energy to a wireless sensor node for real-time appliance control. To prevent breakage, an active bar is fixed, connecting the transmitter sensor to the piezoelectric harvester. Yingyong et al. (2021) [47] investigated initial electrical performance of the Energy harvesting floor tile (EHFT), without adjustments for pedestrian parameters. Mechanism of EHFT employed single piezoelectric cantilever or 44 of them connected in parallel. The lower voltage in the first stage is attributed to the spring counteracting the pressing force on the cover plate, shows in figure 4(c). Panthongsy et al. (2018) [48] designed a prototype of a 24 unimorph piezoelectric cantilever to optimized and validated the design of the energy harvesting floor tiles. The prototype mechanism involved clamping one end of the PZT cantilever to a support and applying DC voltage, while the free end experienced vertical displacement using a rack-and-pinion scale, indicating over-bending through the observed voltage at the free end. Huang et al. (2022) [49] employs cylindrical thickness-polarized PZT-5H elements from the 46th Research Institute of China Electronics Technology Group, Inc., as the key components of the piezoelectric energy harvesting (PEH) device. To address the operational mechanism and the pure pressure environment within the roadway, this research compared to other types of PZT ceramics and structural forms, PZT-5H piezoelectric ceramics in cylindrical configurations consistently exhibit superior piezoelectric properties under traffic loads. Yuan et al. (2022)[50] focuses on pavement PZT5 A materials and the design considerations for a device intended to be fully rolled over by multiple tires. The dimensions of the device are set at 150 mm × 150 mm × 30 mm to ensure effective interaction. The shell material chosen is polypropylene and a waterproof gasket is incorporated between the top plate and the base plate to meet the waterproof requirements for road structures. The device houses nine stacked energy harvesters, emphasizing its potential for energy harvesting applications. Table 1 shown review of the design from the previous study of the piezoelectric energy harvester.

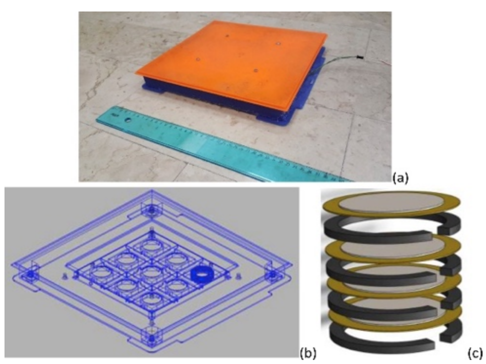


Figure 4a Piezoelectric Tiles [42]

Figure 4b Stack Piezoelectric Tile [43]

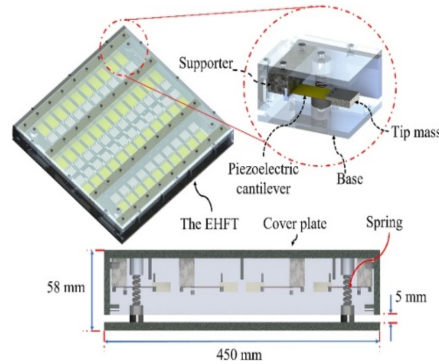


Figure 4c Energy Harvesting Floor tiles [47]

Table 1 Floor tiles of the piezoelectric energy harvester

No.	Product Type	Power Generated	Result Based	Reference
1	Piezoelectric tiles	100 V to 110 V	S&E	Cascetta et al. (2018) [42]
2	Piezoelectric Stack	Walking Condition- 2.53mW- 2.61mW and Jog Condition – 15.8-16.4mw	S&E	Evans et al. (2019) [43]
3	Piezoelectric energy harvester	Average power – 0.0604W/10 footstep	E	Abadi et al. (2018) [44]
4	Footstep based energy harvester	Average output 249.6 mW	E	Selim et al. (2023) [45]
5	Energy Harvesting Floor tiles	Average output 520mW	E	Yingyong et al. (2021) [47]
6	Piezoelectric Energy Harvester floor tiles	Average power of 1.24 mW and 3.49 mJ	E	Panthongsy et al. (2018)
7	Piezoelectric energy harvester	Average power- 0.32mW	E	Huang et al. (2022) [49]
8	Road energy harvester	Average power- 102.4mW	E	Yuan et al. (2022) [50]

4.2 Design of Footstep Harvesting Using Electromagnetic or Motor generator

Cao et al. (2023) [2] designed double-rocker structure converts up and down motion of plate into a unidirectional rotation motion of the shaft. The magnet-coil transduction system is employed to achieve electricity conversion, principle working of DREEH. Chand et al. (2020) [51] proposed system aims to harness kinetic energy from human movement, with a design centered around two tiles placed in high-traffic areas for optimal performance. Each unit comprises two fluid bags interconnected by flow control mechanisms, including unidirectional valves and miniature hydro generators. This process alternates between the two bags, resulting in an energy harvesting paver. Liu et al.(2018) [52] proposed energy harvesting paver which is step force is applied to the rack, the pinion gear undergoes a counterclockwise rotation, driving the shaft's rotation along with it. The one-way clutch engages, facilitating the rotation of gears between the shaft and the generator in a clockwise direction as depicted in Figure 5(a). Jintanawan et al. (2020) [53] compared between prototype 1 and 2 which is prototype-I was equipped with a 24-V-DC generator and employed a rack and pinion mechanism for motion conversion, while Prototype II, an improved version, utilized a lead screw for motion conversion and a 12-V-DC generator as shown in Figure 5(b). Zou et al. (2024) [54] proposed the BEHF-SRM design features modules for line-to-rotation, up-frequency and unidirectional drive, and electromechanical conversion. It employs a torsion bar to convert vertical motion to rotational motion, reducing transmission mechanism space and allowing more energy harvesters in confined areas. A compact mechanism of screw, gear, ratchet, and pawl enables up frequency, bidirectional drive, and unidirectional rotation to rotational kinetic and elastic potential energy, followed by the gradual conversion of rotational kinetic energy into electrical energy. Ismail et al. (2020) [53] proposed system operates through the utilization of external force, primarily generated by a walking person's footstep on a designated power-generating tile. The system harnesses potential energy stored in springs, which is released when the footstep is lifted, causing a reciprocating movement in the power-generating tile. This reciprocal motion drives a pinion to rotate, imparting rotational motion to an attached shaft. To ensure unidirectional rotational motion, a mechanical clutch is employed. The rotational speed of the shafts is controlled and increased progressively using bevel gears with varying teeth numbers. The final shaft's rotational speed is carefully adjusted to match the requirements of a connected generator, specifically an alternator. This alternator produces power, subsequently stored in an energy storage system comprising a sealed lead-acid battery and a charge controller. Table 2 shows the floor tiles power efficiency of the electromagnetic system employed in the previous investigation.

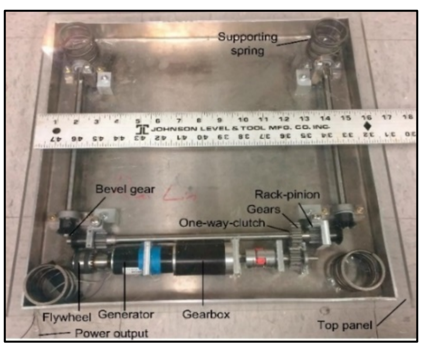


Figure 5a Prototype of the energy harvester paver [52]

Figure 5b Prototype of Energy harvester [53]

Table 2 Floor tiles of the electromagnetic and motor generator energy harvester

No.	Product Type	Power Generated (Watt)	Result Based	Reference
1	Double rocker structure Electromagnetic energy harvester	Maximum voltage of 54.4 V and the output power of 1.034 W	S&E	Cao et al. (2023) [2]
2	Footstep hydro generator energy harvester	Average output power of 1.4 W per step	S&E	Chand et al. (2020) [51]
3	Modular energy harvester paver	Average electrical power of 3.6 W, with a peak value of 12 W	S&E	Liu et al. (2018) [52]
4	Footstep energy harvesting paver	Average power of 520 mW) per footstep	S&E	Jintanawan et al. (2020) [53]
5.	Electromagnetic floor energy harvester	Maximum output power of 11.99 W	S&E	Zou et al. (2024) [54]
6.	Mechanical power generation using footstep	Maximum output 34W	E	Ismail et al. (2020) [55]

4.3 Design of Footstep Harvesting Using Photovoltaic (PV) Cells and Hybrid

The extraction of energy from light has found application in powering portable consumer products, wherein photovoltaic (PV) cells are employed to convert solar or ambient light energy into electric power. Primarily, semiconductor materials are utilized to generate currents and voltages through the absorption of light, a phenomenon referred to as the photovoltaic effect. Zhang et al. (2023) [56] introduces for a photovoltaic-thermal (PVP) system to harvest energy from the road. Three layers surface ground layer, base/subbase, and subgrade are examined to comprehensively analyse the ground influence in the PVP module layout. Tempered glass sheets on the front and rear sides of the PV cell enhance structural strength and protection, while front surface patterns improve anti-skid properties. The damp layer, utilizing air and epoxy resin (EP) backfilling materials, replaces the hollow structure for enhanced support, with asphalt-concrete chosen for the surface ground layer as depicted in Figure 6(a). Zhou et al. (2021) [57] proposes the concept of solar self-powered wireless charging pavement, presenting a conceptual design and expanding its implications to introduce the concept of a road energy internet. The aim is to contribute innovative ideas for intelligent transportation construction and offer solutions for widespread adoption. Hu et al. (2022) [58] designed of the solar pavement panel, utilizing transparent resin-concrete, is illustrated in Figure

6(b). The panel comprises transparent resin-concrete, an unsaturated polyester resin protective layer, waste glass, and an integrated solar panel. The transparent resin-concrete fully encases the solar panel module, enhancing structural stability. Sunlight incident on the module surface is converted into electricity through the photovoltaic action of the embedded solar panels, facilitated by the transparent resin-concrete layer. Zhou et al. (2021)[41] designed a prototype for a Pavement Integrated Photovoltaic/Thermal System (PIPVT. A coolant pipe circulating cold water to assist solar cells in mitigating excessive heating, thereby enhancing power generation efficiency by minimizing operating temperatures. The PIPVT design aims to improve overall solar utilization efficiency. Efthymiou et al. (2016) [59] focuses on mitigating urban heat islands through the incorporation of photovoltaics in pavements. An experimental setup is designed to monitor the performance of PV pavements, placed atop a metallic construction with space beneath for essential equipment. Two different PV panels are used, which is triplex security glass with a nonslip silk screen, PVB standard 1.14 mm placed 5 cm above the PV panels for protection. Dezfooli et al. (2017) [60] designed solar pavement consists of four components: an asphalt layer for surface load bearing, two rubber layers embedding solar cells, an electric system designed and maintained by one rubber layer, and a surface porous layer for drainage and solar cell protection. The research includes a feasibility study, material selection, electrical and structural design, prototype construction, laboratory tests, and a comparative analysis of prototypes considering electrical, resistance potential, skid resistance, and drainage aspects. Nussbaum (2016) [61] introduce SR3 product is a hexagonal paver, approximately 26" by 30", designed for road pavement as depicted in Figure 6(c). Its proprietary design includes half-pavers for straight edges and quarter-pavers for corners. The tempered glass layers encase the central layer containing electrical, heating, photovoltaic, and computer processing components. The polymer layer, more resilient than previous models, seals climate-sensitive components, bonds glass layers, and transfers loads to the concrete base. Each paver is secured to the foundation with vented clips, minimizing interference with photovoltaic cells, ensuring water runoff, and reducing the risk of slick roads. Table 3 shows the efficiency of the PV prototype from the previous researchers.

Figure 6a Outdoor test for PV model [56]

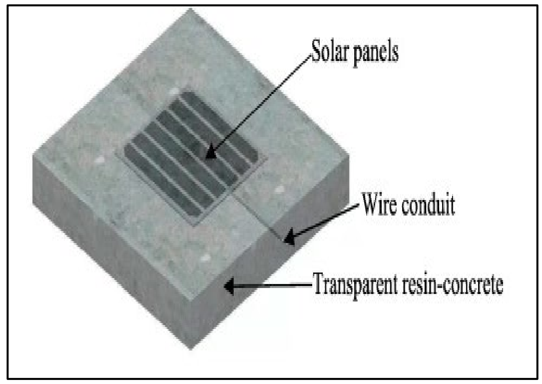


Figure 6b PV pavement [58]

Figure 6c. Roadway photovoltaic[61]

Table 3 Floor tiles of the photovoltaic (PV)

No.	Product Type	Power Generated (Watt)	Result Based	Reference
1.	PV pavement	PV output at approximately 1.08 and 1.01kWh/Wp	S&E	Zhang et al. (2023) [56]
2.	Design PV	-	-	Zhou et al. (2021) [57]
3.	PV Pavement	PV output power 1.4Kwh/day	E	Efthymiou et al. (2016)[59]
4.	Solar pavement	PV output power 1000 W/m^2	E	Dezfooli et al. (2017) [60]
5.	Photovoltaic Pavement	-	E	Nussbaum et al. (2016) [61]

5.0 ECONOMIC AND MATERIAL CONSIDERATION

Within this section, an in-depth exploration is conducted on the cost analysis of components and materials utilized in the manufacturing of energy harvesting systems across various mechanisms. These mechanisms include piezoelectric energy harvesters, electromagnetic coil mechanisms, and photovoltaic energy harvesting systems. This thorough investigation draws upon insights derived from a meticulous review of 19 scholarly journals. Additionally, the discussion extends to the economic considerations associated with this energy harvesting technologies, shedding light on their financial implications and providing a comprehensive understanding of the cost dynamics within the field.

5.1 Material Consideration For Piezoelectric Harvester

The selection of piezoelectric materials holds paramount significance in maximizing energy harvesting efficiency. However, this process necessitates careful consideration of several critical factors, including the cost of production and in terms of material properties of the piezoelectric. A comprehensive evaluation of these aspects is imperative for informed decision-making in the development of efficient energy harvesters. Piezoelectric materials manifest in diverse forms, ranging from high-output single crystals, such as the renowned piezoceramic lead zirconate titanate (PZT) S. Leng et al. (2023) [62], to microscale fiber composites (MFC) H. A. Sodano, G. Park, and D. J. Inman (2004) [63], film-based polyvinylidene fluoride (PVDF) A. Truitt and S. N. Mahmoodi (2013) [64], and PMN-PZT X. Wang et al. (2022) [65]. It is noteworthy that piezoelectric materials commonly display anisotropic characteristics, whereby material properties vary based on the direction of applied forces, as well as the orientation of polarization and electrodes. This inherent anisotropy underscores the need for a nuanced understanding of material behaviour for optimal utilization in various applications.

The tile incorporates Lead Zirconate Titanate as its piezoelectric material, converting mechanical energy into electrical energy through nine stacks situated beneath the tile's upper surface. Each stack is comprised of five piezoelectric diaphragms (buzzers) spaced by rings to facilitate vibration. Previous research in the field of energy harvesting from floor tiles has predominantly focused on the use of polyvinylidene fluoride (PVDF) and lead zirconate titanate (PZT). The significance attributed to these materials highlights their central role in exploring energy harvesting possibilities from floor tiles. The subsequent sections will elaborate on the key discoveries and insights gleaned from these studies, providing a comprehensive understanding of the effectiveness and limitations of PVDF and PZT in the context of floor tile energy harvesting systems [42].

After careful consideration, it is concluded that PZT-5H material stands out as an ideal choice for applications in pavements when compared to PZT 4 and PZT 8. The voltage generated by PZT material exhibits a correlation with the loading frequency. Within the frequency range of 1 to 5 Hz, there is a notable increase in voltage, while the voltage rise is more gradual from 5 to 10 Hz. PZT material performs more favorably under the d-33 mode. Beyond a loading frequency of 5 Hz, PZT-5H demonstrates both higher voltage and a greater relative dielectric constant. Regarding size, PZT-5H displays a larger capacitance, enabling it to generate more power under the same load. In a comparative analysis, PZT-5H, operating under the d-33 mode, produces more power per unit volume, making it better suited for piezoelectric energy harvesting. The crucial parameter for PZT, the piezoelectric modulus d33, ultimately determines its capacity for energy generation [66].

5.2 Material Consideration For Energy Harvester Electromagnetic Coil

The power output in a coil and magnet system, accounting for internal coil resistance, is influenced by the number of coil turns (N), where increasing N enhances power output due to a greater induced electromotive force (EMF); magnetic field density (B), as higher density contributes to increased power output by affecting magnetic flux passing through the coil; cross-sectional area of the coil (Scoil), where a larger area generally results in higher power output by impacting the intercepted magnetic flux; angular velocity of the magnet (ω), as a higher velocity leads to increased power generation by affecting the rate of magnetic flux change; and phase position of the magnet (α), as optimizing alignment with the coil enhances power output, along with the consideration of internal coil resistance, which can impact power output by causing losses and reduced efficiency [67].

5.3 Material Consideration For Photovoltaic Pavement

Prior investigations have evaluated the economic viability of TEG-powered harvesters using the LCOE methodology. The initial study Datta et al. (2017)] [68] compared TEG to established PV harvesters, resulting in LCOE estimates of 0.89 $/kWh for a 7 °C thermal gradient and 0.344 $/kWh for PV, revealing potential despite cost disparities. However, the absence of analyses on the expenses related to installing PV panel surfaces on roadways, exemplified by the SolaRoad test site's $3.7 million construction cost for just 70 meters, underscores the difficulty in accurately comparing costs for roadway PV installations on an industrial scale, as noted in the literature review [1].

6.0 DESIGN OF CIRCUIT DIAGRAM CONFIGURATION

Kim et al. (2018) [46] presented floor tile demonstrates a composition of multiple piezoelectric equivalent circuits. When pressure is applied to the floor tile, mechanical energy is converted into electrical energy, rectified, and used to charge a capacitor. This harvested energy serves as the power source for a wireless sensor node instead of the conventional lithium-ion battery. The wireless transmitter node (eZ430-RF2500T) is activated and transmits on/off data to a wireless receiver (eZ430-RF2500T). Ultimately, a relay circuit controls the connection between a 220 V commercial power source and a light, enabling the light to be turned on and off.

Yingyong et al. (2021) [47] proposed the process of harnessing piezoelectric energy from the 44 cantilevers, a pivotal step included linking them to a rectifier to convert the produced alternating current into a practical direct current. The harvested energy was judiciously stored through the utilization of a capacitor, functioning as a dependable reservoir. To evaluate the system's effectiveness, a thorough measurement methodology was implemented. Employing the Micsig model STO1104C oscilloscope, the voltage variations across the capacitor were meticulously measured and closely monitored.

Panthongsy et al. (2018) [48] designed a full-wave bridge rectifier, composed of small-signal Schottky diodes (BAT 46), was employed for each PZT cantilever and electrically connected in parallel with other rectifiers. The parallel configuration was utilized to combine the output currents from all PZT cantilevers.

This arrangement was necessary because each PZT generated a high voltage but only a low current. Three types of assessments were conducted: the evaluation of energy harvesting performance for one and then 24 PZT cantilevers, the impact on energy harvesting performance based on the placement location of footsteps, and the energy harvesting performance of the tile in a real-world scenario. Initially, the energy harvesting performances of one PZT cantilever and 24 PZT cantilevers were examined under various load resistors.

Chand et al. (2020) [51] design control circuit is tasked with directing the generated energy to the battery. The charge controller's output voltage is adjustable using the potentiometer to match the requirements of the battery intended for charging. The Schottky diode D1 serves the purpose of preventing any reverse flow of current to the generator. The circuit also has the capability to be directly linked to a load, such as charging phones. However, a limitation of this particular charge controller design is the presence of a voltage drop across the two diodes and the voltage regulator.

Jintanawan et al. (2020) [53] suggests a method for storing the generator's power in a 6-V, 4.5-Ah battery using a two-stage power converter. Initially, an active bridge rectifier is employed to convert AC voltage into DC voltage, taking advantage of MOSFETs with exceptionally low turn-on resistances and junction voltage drops, thereby ensuring increased efficiency. Subsequently, a buck-boost converter is utilized to regulate the variable DC voltage from the rectifier for the battery. This converter operates based on a matching-impedance control scheme, optimizing power transfer. In this scheme, the reactance term associated with inductance is considered negligible and is thus excluded from the calculated impedance.

Khuwaja et al. (2015) [69] proposed the integration of current and voltage sensors along with a relay connected to the Arduino Mega 2560 board. Voltage measurement involves utilizing a voltage divider circuit, where two resistors are strategically placed in series to effectively divide the voltage. A charge controller is implemented to ensure proper battery charging and to supply voltage to the load. The connection of the current and voltage sensors and the relay to the Arduino Mega 2560 board.

7.0 FUTURE CHALLENGE

The current body of research falls short in addressing the development of a comprehensive floor tile system that seamlessly incorporates all three essential elements: piezoelectric, photovoltaic, and electromagnetic functionalities. Delving into this unexplored territory not only opens up new prospects for future investigations but also holds immense promise for practical applications. In environments characterized by abundant sunlight, the photovoltaic component within the proposed system can effectively capture solar energy. Simultaneously, the incorporation of piezoelectric and electromagnetic mechanisms, triggered by human footsteps, provides a unique and dual-source energy harvesting capability. This innovative integration not only enhances the system's efficiency but also offers a compelling avenue for further in-depth exploration and development. The potential benefits of such a multifaceted approach to energy harvesting make it a worthwhile subject for extended research and experimentation in the field.

As outlined in existing literature, electromagnetic energy harvesting technology, incorporating various mechanisms, demonstrates considerable promise for integration into pavements. This technology not only provides an efficient and reliable means of energy generation but also proves to be cost-effective and renewable, presenting a particularly advantageous solution in remote areas lacking access to the conventional power grid. The versatility of electromagnetic energy harvesting positions it as a promising avenue for sustainable energy solutions in diverse environments.

Piezoelectric materials have the capability to generate electrical power through vibrations or stresses induced by passing vehicles and wind energy. Typically, they produce high voltages with low amperage, resulting in a relatively lower power output. According to available literature, this technology proves suitable for providing electrical energy to operate low-power systems. The literature underscores the significant potential of these systems for energy harvesting applications. The power output and efficiency of such systems depend on various factors, including the type of piezoelectric material used, encompassing its shape, size, and dimensions, as well as the operational mechanism and the specific electric circuitry employed. The intricate interplay of these factors highlights the nuanced considerations in optimizing piezoelectric energy harvesting systems for enhanced performance and sustainability.

While photovoltaic (PV) panel technology has advanced significantly, its full applicability for installations on pavement surfaces remains unrealized. The predominant challenges lie in ensuring structural resilience to withstand vehicular loads, providing adequate friction for safe vehicle movement, and achieving surface transparency to capture optimal solar radiation exposure. The potential benefits of such a multifaceted approach to energy harvesting make it a worthwhile subject for extended research and experimentation in the field.

8.0 CONCLUSION

All these energy harvesting technologies provide environmentally friendly and renewable energy, making them suitable for applications in rural areas, such as powering LED lights, children's playgrounds and pedestrian zones. Among these technologies, electromagnetic, photovoltaic (PV), and piezoelectric harvesters appear to be the most viable for implementation. While their power generation potential may be lower compared to the more established PV technology, they offer the advantage of unobtrusive installation by embedding them into pavement layers. As the push for smarter energy harvester intensifies, evaluating the economic efficiency of these harvesting technologies becomes crucial for broader implementation, ensuring wider distribution and a reduction in unit costs. This re-evaluation is vital to fully exploit the potential of these technologies on a larger scale and meet the growing demand for sustainable energy solutions in roadway infrastructure.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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