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Energy Harvesting for Applications in Road Construction and Bridge Engineering

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ABSTRACT

The objective of this research is to review the available energy harvesting techniques applied in road construction and bridge engineering, such as photovoltaic cells, solar collectors, geothermal energy and thermoelectric, electromagnetic and piezoelectric systems. Energy harvesting is a highly promising technique that can contribute to the production of clean and renewable energy and improve the sustainability of infrastructure. The energy collected through these techniques can subsequently be used as electrical power, provide heating or cooling, facilitate ice melting, power wireless sensors and monitor the structural conditions of various constructions. Each energy harvesting technology is examined in depth, including its operating principles, application examples, prototype developments, and significant findings reported in the literature.

Keywords: Energy Harvesting Techniques; Energy Harvesting Technology; Clean Energy; Renewable Energy; Sustainability; Road Construction; Bridge Engineering; Environmental Pollution; Energy Production; Infrastructure.

1. Introduction

Energy is the cornerstone of the development of human civilization. The continuously increasing demand for energy, along with the overconsumption and depletion of existing energy resources, is a serious problem the world faces today. In addition, environmental pollution caused by excessive use of fossil fuels is constantly increasing. Therefore, it is urgent to identify, develop and implement new energy production techniques that are sustainable and environmentally friendly.

The discovery and utilization of green and renewable energy sources, including hydro energy, wind energy, solar energy, ocean energy and bioenergy, is one of the critical challenges the world faces for sustainable development. Oil, coal, hydropower, natural gas and nuclear energy are the most commonly used energy resources for power generation today.

Energy harvesting is a promising technique that can generate renewable and clean energy while improving infrastructure sustainability [1]. Energy harvesting technologies capture unused or wasted energy and convert it into a more usable form. Solar, wind, hydroelectric, thermal and kinetic energy are the common energy sources currently utilized and harvested [2]. In recent years, researchers have begun to harvest electrical energy from the environment using various techniques, such as piezoelectric, thermoelectric, electromagnetic and photovoltaic methods [3].

1.1. Study Objectives

Accordingly, the objectives of the herein study were the following:

1) To enquire the technologies of harvesting solar energy for roadway applications and constructions.

2) To investigate the usage of thermoelectric generators (TEGs) in roadway applications and constructions.

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3) To enquire the usage of geothermal energy in roadway applications and constructions.

4) To investigate the usage of piezoelectric energy harvesting for roadway applications and constructions.

5) To enquire the technologies of energy harvesting for sensor applications in bridges.

2. Energy Harvesting for Roadway Applications

Roads are one of the most essential urban infrastructures, playing a crucial role in connecting communities and facilitating human mobility. Traditionally, roads have been considered as construction platforms designed to bear traffic loads. Road surfaces and bridge decks are constantly exposed to vehicle loading and solar radiation, causing mechanical vibrations and thermal gradients within the pavement layers. Mechanical energy can be converted into electrical energy through a magnetic field for electromagnetic materials or a strain field for piezoelectric materials [4], while solar energy can be harvested through photovoltaic cells, heat flow or thermoelectric field. Therefore, wasted energy in the pavement can be harvested and converted into usable energy with a variety of applications. Figure 1 illustrates all available energy harvesting technologies that can be applied in roadway infrastructure [5].

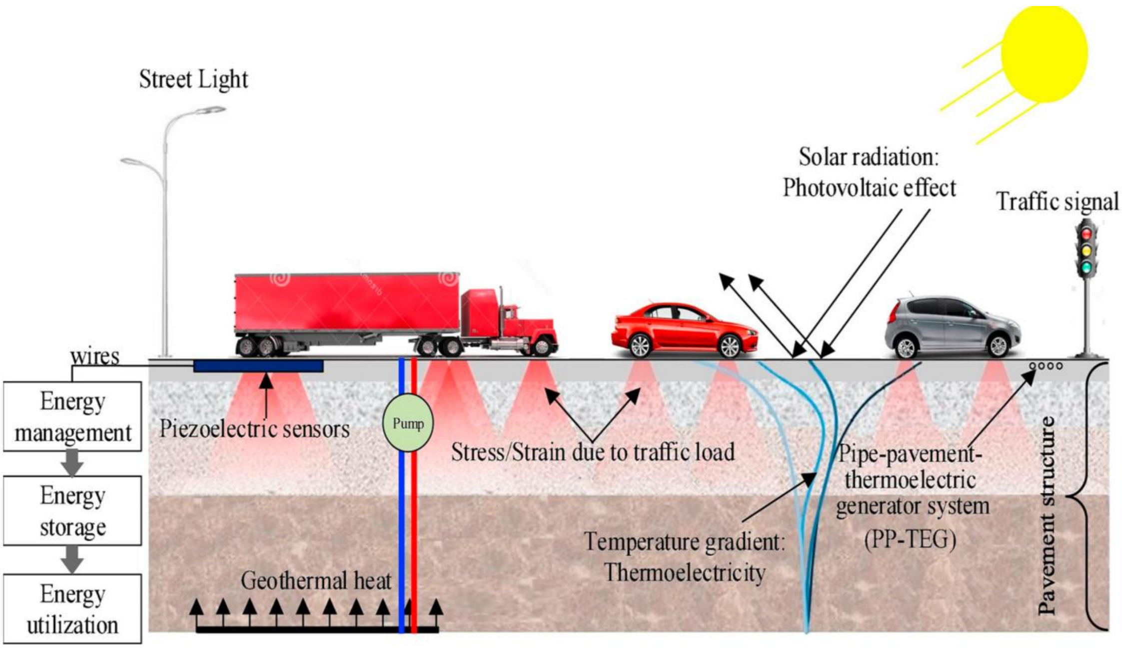

Figure 1. Available energy sources on roads [5]

The energy harvesting system typically consists of an energy generator, an electrical circuit and an energy storage device. Once the harvested energy from the environment is converted into electrical energy, the electrical circuit amplifies and regulates the generated voltage [6]. The harvested energy can be stored in a rechargeable battery or a supercapacitor. Depending on the principle of each harvesting technology, the amount of energy production varies significantly. A large amount of energy can be directly utilized for electricity supply and the power grid [7]. On the other hand, a relatively small amount of energy can be used for heating the road surface or bridge deck for de-icing, lighting, or powering traffic devices.

In addition, energy harvesting could provide continuous power support for in-site monitoring sensors installed on roads and bridge decks [8]. Traditional sensors used for on-site monitoring of civil infrastructure conditions include accelerometers, displacement sensors, force sensors, resistance strain gauges, and optical fibers. Recently, wireless sensor networks have been widely used for structural health monitoring (SHM); however, one of the main limitations of wireless sensors is the power supply for long-term application. A piezoelectric sensor with a well-designed packaging system can function as a smart material for SHM [9]. For example, highway bridges are continuously subjected to vibrations due to moving vehicles and wind. The dynamic response of bridges induces strains in the electromagnetic or piezoelectric sensors attached to bridge components, which can be used to power the sensors [10].

2.1. Solar Energy Harvesting

The photovoltaic (PV) cell is used to convert solar radiation into electrical energy. The solar cell consists of a P-type semiconductor and an N-type semiconductor.

When sunlight reaches the semiconductor materials of a PV cell, free electrons are forced to flow in a specific direction [11]. Negatively charged electrons move towards the N-type semiconductor, while positively charged electrons move towards the P-type semiconductor. The operating principle of a PV cell is presented in Figure 2. The flow of moving electrons generates an electric current when connected to an electrical load.

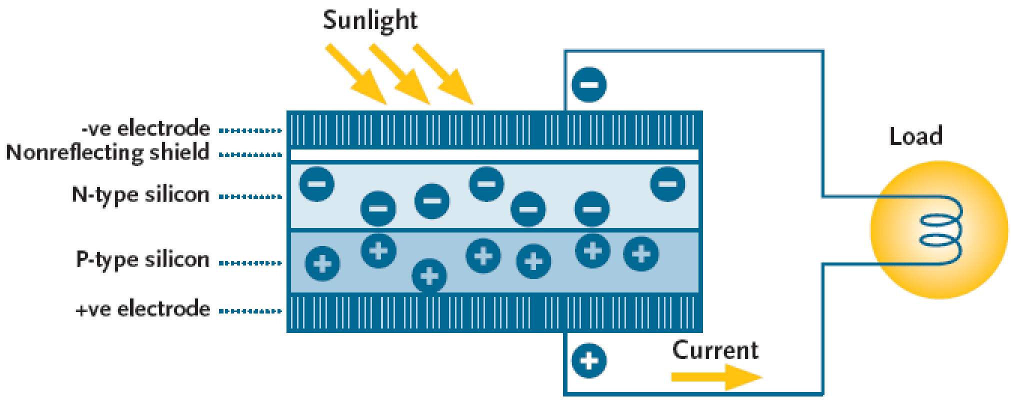

Figure 2. Operating principle of photovoltaic solar cells [11]

Several studies have investigated the applications of photovoltaic cells on roads for solar energy harvesting [12]. Jung et al. (2017) examined the feasibility of solar energy collection using road-integrated photovoltaic technologies. The authors reported that the application of thin-film photovoltaic cells on the road surface presents challenges due to difficulties in maintaining durability under various traffic loads and weather conditions. Therefore, new designs of thin-film solar cells with suitable surface characteristics are required for use as a road surface [13].

The first field application of pavement photovoltaic cells in the U.S. was a prototype solar parking lot funded by the Federal Highway Administration (FHWA) in 2009. In 2014, the company SolaRoad constructed a 100-meter-long bicycle path with solar collectors covered by a 1 cm thick top layer of glass in the Netherlands [14]. The bicycle path generated 350 kWh of electricity in one year. SolaRoad demonstrated that the flat angle of the solar panel would produce only one-third of the electricity generated by conventional rooftop photovoltaic panels.

In 2015, the company Colas, in collaboration with the French National Institute of Solar Energy, claimed to have developed a new type of photovoltaic pavement called Wattway [15], suitable for industrial use. The solar cells were reported to be resistant to traffic and slippage, making them viable for use in all types of road infrastructure in the future.

Studies have also found that photovoltaic (PV) pavement surfaces provide an effective solution for mitigating the urban heat island (UHI) effect. Efthimiou et al. (2016) [16] highlighted the contribution of PV pavement to the UHI effect using numerical predictions and a small-scale field experiment [17]. The results showed lower surface and ambient temperatures associated with PV pavement compared to traditional asphalt pavement. Golden et al. (2007) [18] conducted a comparative study to investigate the thermal effects of three different pavement surfaces [19]. The findings indicated that surface coverage with PV panels provided the greatest thermal reduction compared to the fully exposed asphalt pavement surface and the asphalt pavement surface shaded by forestry.

In addition to using photovoltaic technology for energy harvesting from the road surface, other applications, such as noise barriers, also exist. The implementation of photovoltaic noise barriers (PVNB) is increasing along highways and railways worldwide. This technology is one of the most effective applications of photovoltaics, providing both energy generation and noise protection for surrounding areas [20]. Nordmann et al. (2004) [21] studied the potential of PVNB in six European countries. The authors observed that these technologies generated 800 MWh of electricity, with the potential to expand to 680 GWh annually [22].

It is noted that solar energy collection can be maximized only under direct sunlight during a specific period of the day. Productivity is limited in low-light conditions, such as on cloudy days or in tunnels. Although PV pavement is environmentally preferable to conventional pavements, further research and development efforts are required to make it a feasible option for everyday use due to its high cost and resistance under varying weather and traffic conditions [23]. A solar collector system consists of a network of pipes beneath the pavement, through which a circulating liquid flow. As the pavement absorbs radiation from the sun and the atmosphere, its temperature increases, and heat is transferred to the fluid within the piping system due to temperature gradients. There are three primary heat balance processes involved in the pavement solar collector system: conduction, convection, and radiation (Figure 3).

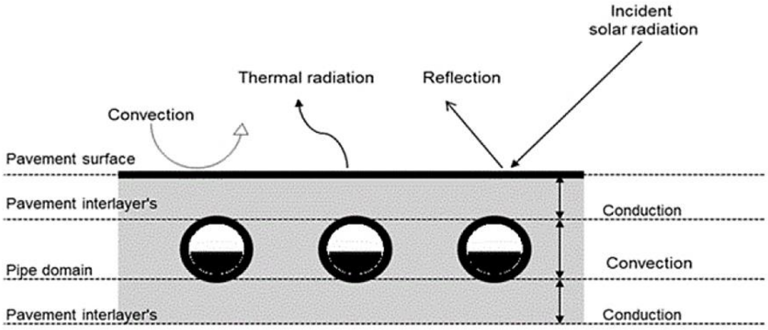

Figure 3. Heat transfer mechanisms in asphalt solar collectors [24]

Conduction occurs between the pavement and the pipe walls. Energy transfer through convection happens when there are temperature differences between the ambient air, the pavement, the pipe walls and the circulating fluid inside the pipes [25]. Radiation through electromagnetic waves can occur without any material medium, including the transfer of solar radiation to the pavement and thermal radiation between the ambient atmosphere and the pavement.

The heat captured by the piping system can be used in thermoelectric generators to produce electricity or stored in energy tanks [26]. During winter, the stored heat can be utilized for melting snow on roads, generating electricity, and heating nearby buildings. Another advantage associated with the pavement solar collector system is its ability to reduce the urban heat island (UHI) effects in metropolitan areas by decreasing pavement temperatures [27]. The cooling effect also helps to slow down pavement deterioration and maintain pavement performance under high-temperature weather conditions. One of the pioneering applications of solar pavement collectors is the snow-melting system known as SERSO in Switzerland, which began operation in 1994 [28]. The SERSO system has demonstrated the feasibility of storing seasonal solar energy in underground thermal energy storage systems. It consists of 91 borehole heat exchangers (65 meters deep) that maintain the bridge deck surface temperature above 3°C during winter. The electrical energy was used solely for circulating water within the pipes, without the use for heat pumps [29].

Given that pavement solar collector technology is feasible for water heating applications, recent studies have aimed to optimize system configurations. Researchers have proposed modifying the thermal properties of pavement and solar energy collection systems in order to increase the efficiency of solar collectors. Either carbon fiber powders or graphite have been used to increase the thermal conductivity of asphalt concrete and improve the efficiency of solar collectors [30]. Although metal pipes have high thermal conductivity, plastic pipes are commonly used to prevent corrosion and structural failure. Water and water-antifreeze mixtures are usually used as heat exchange fluids in solar collector systems [31]. A study indicated that increasing the flow rate could accelerate the heat transfer process [32]. However, the research conducted by Chen et al. (2016) demonstrated that heat transfer efficiency does not necessarily improve with a higher flow rate [33].

The performance of solar pavement collectors is affected by geometric and operational parameters, such as pipe spacing, depth, and fluid flow rate [34]. Matrawy and Farkas (1997) conducted a comparative study of pipe configurations and concluded that two parallel plate collectors provided the highest efficiency among three options, which included parallel and serpentine arrangements [35]. Chen et al. (2011) compared different pipe spacings and found that pavement temperature decreased more rapidly with closer pipe spacing. They also conducted a study analyzing the snow-melting performance of asphalt solar collectors [36]. The best results, in terms of melting time and operating costs, were achieved when the pipes were placed at a depth of 4 cm or 10 cm with a spacing ranging from 0.18 m to 0.4 m [37].

However, the liquid-based piping system has several inevitable limitations. First, pavement integrity may be damaged due to the installation of the piping system within it. Second, irregular pipe leaks may occur with both metal and plastic materials. Third, the piping system increases the difficulty of pavement maintenance and rehabilitation [38]. To mitigate the issue of fluid leakage, Garcia and Partl (2014) proposed the use of parallel air ducts instead of liquid-filled pipes. Their study concluded that the airflow rate, driven by the temperature difference between the air and the pavement, is a key factor in improving the overall efficiency of the system [39]. At the same time, to overcome the limitations of solar collector piping systems, Muñoz et al. (2013) suggested using a highly porous intermediate layer beneath the pavement surface instead of the piping system. The authors noted that system performance could be constrained by low airflow velocity, although further research is needed for practical applications [40].

Recently, numerical simulations for optimizing solar collector systems have examined the interaction between building geometry and urban environments [41]. Nasir et al. (2015) conducted computational fluid dynamics (CFD) analysis to determine the impact of building configuration on the thermal performance of pavement solar collectors. The results indicated that pavement solar collectors were more efficient in urban environments than in rural settings [42]. Later, the authors used CFD to optimize the design parameters of pavement solar collectors in urban and peri-urban areas. Numerical simulations, combined with experimental validations, have proven to be effective methods for optimizing solar collector systems [43].

2.2. Thermoelectric Generator (TEG)

The thermoelectric generator (TEG) harvests energy from environmental thermal changes. TEG can utilize the temperature differences between pavement layers to generate electricity based on thermoelectric principles [44]. The direct conversion of thermal energy into electrical energy makes thermoelectric generation one of the most promising technologies for efficient thermal energy harvesting. Discovered by T.J. Seebeck in 1821, the Seebeck effect has been widely used in most thermoelectric generation technologies [45]. The Seebeck effect is defined as the generation of an electric field when there is a temperature gradient across the two ends of a thermoelectric generator device. The temperature gradient of the conductor and the production of electric current are reversible. The TE unit usually consists of two parallel semiconductors, N-type and P-type, with a heat source and a heat sink on each side (Figure 4).

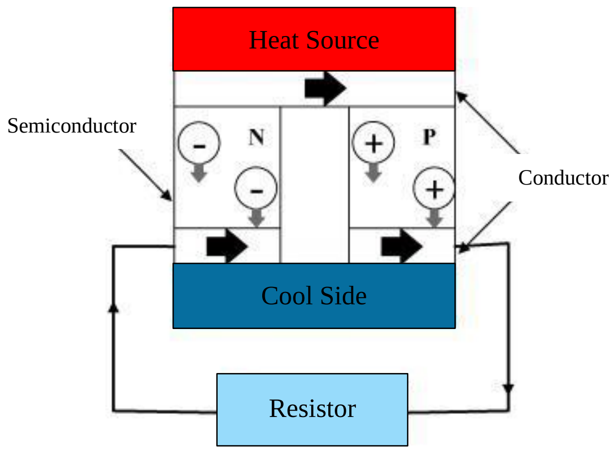

Figure 4. Operating principle of the thermoelectric generator

According to the Seebeck effect, high Seebeck coefficient, low thermal conductivity, and low electrical resistivity are required to optimize the conversion efficiency of a thermoelectric generator. Low thermal conductivity and electrical resistivity ensure minimal energy loss caused by heat conduction and Joule dissipation [46]. Thermoelectric semiconductors are conventionally used to overcome the limitation of isotropic metals, whose

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improvement is restricted by the Wiedemann-Franz law. The main disadvantage of this technology is its low efficiency, but the use of new materials in TEG manufacturing could improve the efficiency.

Hasebe et al. (2006) proposed thermoelectric generators utilizing solar thermal energy collected by the piping system beneath the pavement. The thermal energy at the hot end of the thermoelectric generator (TEG) originated from the water circulating in the heating pipe, while the cooling pipe transported cool water from an inlet [47]. The concept of the pipe-pavement-thermoelectric generator system is illustrated in Figure 5. Laboratory experiments demonstrated that the output power was at its maximum resistance value of 30 Ohms and increased with the flow rate. The results also indicated that the maximum surface temperature of the pavement with the system was 30°C, compared to the conventional pavement temperature of 60°C [48].

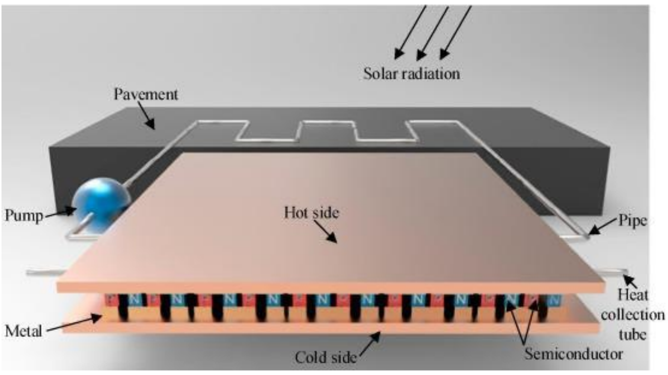

Figure 5. Concept of a pipe-pavement-thermoelectric generator system

Wu & Yu (2013) developed a thermoelectric energy harvesting system to power pavement monitoring sensors [49]. Unlike the piping system proposed by Hasebe et al. (2006), their system consisted of a commercial thermoelectric module connected to aluminum plates and rods at both ends to transfer heat between the pavement surface and the subgrade soil [47]. The authors conducted laboratory experiments using LED light to simulate the sensor load with a temperature gradient of 20 K across the thermoelectric module. The results showed that the output power was approximately 0.05 mW, with an overall system efficiency of 2.05%. Error! Reference source not found. Later, Wu & Yu (2013) used computational simulations to study the application of thermoelectric generation in pavement to optimize the system [49]. The system was estimated to provide 0.02 W and 1000 J per day, which was sufficient to power pavement monitoring with an integrated circuit (IC) sensor device [50].

Jung et al. (2012) [24] conducted experiments to investigate the factors affecting the system performance. The thermoelectric system was similar to that of Wu & Yu (2013) [49]. Thus, four types of TEG with different properties were compared [51]. The authors proposed matching the electrical and thermal impedance for selecting an efficient TEG and evaluated the heat exchanger with varying thermal resistance and insulation conditions. The optimal combination of TEG device produced over 40 mW of electrical power. The study supported the idea that the TEG had a power output approximately 800 times higher than that in the most recent study using thermoelectric generation in pavement energy harvesting [52].

Liang and Li conducted laboratory experiments using asphalt samples heated by an infrared heat lamp to create temperature gradients. The results showed that the optimal depth for the TEG was between 20 mm and 30 mm

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below the surface, considering system efficiency and varying temperature gradients. An outdoor experiment using four TEGs demonstrated that the electrical energy generated in one day was 2,592 J [53]. The authors also carried out laboratory experiments on the dynamic stability of the combine harvester within the pavement and found that the TEG at a depth of 20 mm exhibited good durability.

Datta et al. (2017) evaluated the prototype of a thermoelectric energy harvesting system through finite element analysis, laboratory tests, and field experiments [54]. The results showed that the copper plate could achieved the highest temperature gradient of 16°C, with the optimal TEG design depth at 180 mm. Laboratory tests indicated that the average energy efficiency of the two selected prototypes was 1.67 mW/°C. Field tests demonstrated that the output power ranged from 4 mW to 6.5 mW. The authors also provided preliminary cost analysis results, estimating material costs at $190 and $94 for the prototypes with two and four TEGs, respectively [55].

Although the TEG technology applied to pavements is theoretically feasible, future research could focus on improving system efficiency through enhanced structural design and optimized material properties of the TEG. Other critical factors include the placement of the thermoelectric harvesting system within the pavement and the exposure of thermoelectric elements to traffic-related hazards.

2.3. Harvesting Geothermal Energy

Geothermal energy is the thermal energy originating from the Earth's depths, meaning the energy naturally stored within the planet. Geothermal heat pumps and underground thermal energy storage play a significant role in the application of geothermal energy. Heat pumps are heat transfer devices that can enhance the heat output of a fluid when receiving geothermal heat input at relatively low temperatures. Figure 6 illustrates the core concept of geothermal energy beneath the pavement surface using embedded pipes [56]. The fundamental principle of the most common heat pumps is vapor compression, where the gas temperature increases when compressed without heat loss. For underground thermal energy storage, the key factor is minimizing energy loss, which is influenced by storage duration, temperature, volume, and the thermal properties of the storage medium.

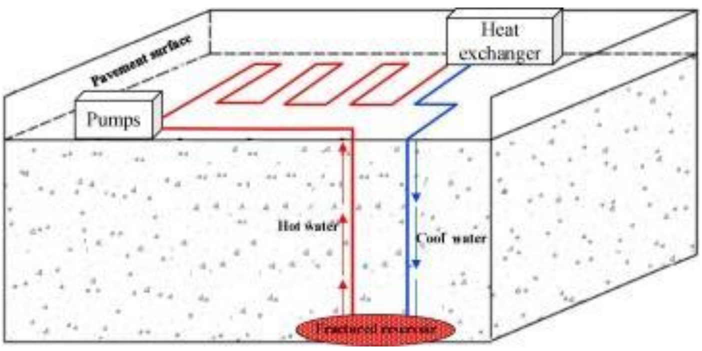

Figure 6. Operating principle of geothermal energy collection

Geothermal water or steam has been used as a heat source for snow melting in the United States since 1948 [57]. The first system was built in Klamath Falls, Oregon, consisting of an iron piping system with a 50% ethylene glycol solution circulating inside. However, after nearly 50 years of operation, external corrosion and severe leakage led to system failure. Nowadays, metal pipes in snow-melting systems are being replaced with plastic pipes to prevent corrosion [58]. Griffin (1982) conducted a study on bridge de-icing using different heat sources, including solar energy and geothermal heat. The heating cost using deep underground water was $37 per square meter, while the cost of heating with solar collectors was $26 per square meter [59]. However, these costs may have changed today due to inflation, discount rates and advancements in technology [60].

Ziegler et al. (2009) designed an airport foot heating system at Greater Binghamton Airport in Johnson City, New York [61]. The project adopted a hydronic radiant heating system, with geothermal heat pumps as the heat source. The report addressed technical aspects of the geothermal heating system and its projected impacts using a life cycle cost analysis (LCCA). The installation and utility costs for the first year amounted to $1,590,502, while the maintenance cost from the second year was $31,741. The results showed that the cost of the geothermal heating system was slightly higher than traditional snow removal methods but provided benefits in terms of safety and environmental impact. The combination of pavement solar collectors with geothermal heat storage is an efficient energy harvesting technology [62]. In Japan, the snow-melting system used underground geothermal energy as a heat source during winter and had a thermal storage tank for storing solar heat collected during summer.

Recently, researchers discovered that using geothermal heat pumps in combination with permeable pavement had the added benefit of improving stormwater quality [63]. Maharaj and Paul (2015) investigated stormwater quality with a geothermal heat source embedded beneath a permeable pavement structure for cooling and heating purposes, using 12 scaled pavement systems [64]. The results showed that significant temperature changes in the pavement due to the cooling and heating processes of the geothermal heat pump reduced the ecological risk of stormwater runoff and the development of pathogenic agents.

Although geothermal heat is an attractive renewable energy source, there are limited studies focusing on the environmental impacts of geothermal energy systems [65]. Shen et al. (2015) evaluated the greenhouse gas (GHG) emissions of a geothermal heating system compared to the traditional snow removal process using chemical deicers and mechanical plowing. The results showed that GHG emissions were lower for the geothermal system when removing one inch of snow from the airport runway [66].

2.4. Piezoelectric (PE) Energy Harvesting

Piezoelectric materials generate electric charges when subjected to mechanical stress or change their geometric dimensions when an electric field is applied. The operating principle of piezoelectric energy harvesting is illustrated in Figure 7. The voltage generated by a piezoelectric material varies over time, resulting in an alternating current (AC) signal, which induces the direct and inverse piezoelectric effects, respectively [67].

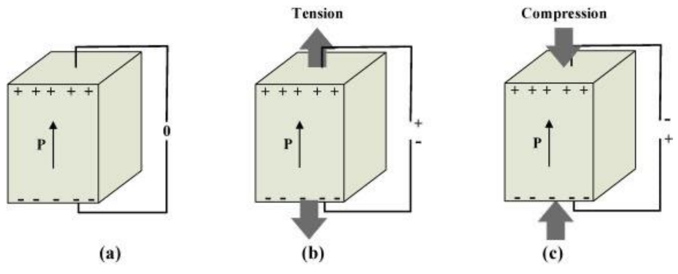

Figure 7. Operating principle of the piezoelectric effect under (a) zero voltage (b) tension and (c) compression

Piezoelectric materials can be classified into the following categories: single crystal materials (e.g., quartz), piezoceramics (e.g., lead zirconate titanate [PZT]), and others. Although piezoelectric materials have different piezoelectric and mechanical properties, the most common ones are polymers and ceramics. Polymer materials are soft and flexible, while ceramics are rigid. Polymer materials produce lower energy compared to ceramics due to their differing dielectric and piezoelectric properties.

There are two methods by which you can increase the amount of electrical energy produced. Firstly, is to increase the applied pressure or strain. Another method is to use the coupling mode more efficiently. There are two possible coupling modes, d31 and d33, depending on the polarization direction of the piezoelectric material in relation to the direction of the applied force. The mode is defined as d31 when the material is subjected to a force perpendicular to the polarization direction, while it is defined as d33 when the force is applied in the same direction as the polarization. The d33 mode provides the highest electromechanical coupling compared to the d31 mode, as experienced by most piezoelectric materials [68].

Many piezoelectric transducer designs have been proposed, such as the cymbal, multilayer, etc. The energy harvesting performance of the piezoelectric transducer is influenced by the material, the geometry of the transducer, and the external loading. Interest in piezoelectric technology based on mechanical energy has increased in recent years due to its high energy conversion efficiency [69]. Although both forces and vibrations induced in the pavement can be used to activate piezoelectric transducers, strain-based energy harvesting is studied more in pavements, while energy harvesting based on vibrations is more studied in bridges.

Chua et al. (2015) examined the potential of PZT energy harvesting in both mechanical and electrical environments using finite element analysis (FEA). They concluded that metallic end caps made of different materials with varying electrical resistance loads had significant effects on energy generation. They also found that increasing the thickness of the steel end caps and the PZT strip resulted in higher power output. The considered cymbal transducer generated approximately 0.46 mW of power under a 50-N force and a 3 MΩ load resistance [70]. On the other hand, Xiang et al. (2016) conducted a theoretical analysis and a parametric study of piezoelectric transducers in the pavement system. They analyzed the effects of damping, the pavement system coefficient and vehicle speed on power output [71].

Roshani et al. (2018) conducted laboratory tests and finite element analysis to simulate static loading on a prototype containing four piezoelectric discs. Each disc was subjected to a pressure of 5 MPa, generating a voltage of approximately 650 V [72]. They concluded that the heavier the load, the shorter the loading duration and that higher traffic speed could significantly increase the output voltage. The effect of pavement thickness on electricity generation was found to be negligible compared to the impact of traffic load.

Field tests have been conducted to evaluate the performance of piezoelectric energy harvesting. Xiong and Wang (2016) developed a piezoelectric energy harvesting (PEH) mechanism and assessed the output voltage and current of the PEH generated under real on-site traffic conditions [73]. They concluded that approximately 15% of the applied mechanical energy was transferred to the piezoelectric materials. Moure et al. (2016) evaluated piezoelectric cymbals embedded in asphalt pavement to optimize energy conversion. The results showed that each piezoceramic cymbal could recover up to 16 μW per heavy vehicle passage. They claimed that a 100-meter road with 30,000 cymbals could generate more than 65 MWh in a year [74]. Papagiannakis et al. [75] developed highway sensing and energy conversion (HiSEC) units, using various configurations and different numbers of PZT rod elements. Different box configurations containing various PZT element shapes were examined. The feasibility of the harvester design was tested in the laboratory to measure the electrical energy output. The results indicated that HiSEC units could be used to power LED lights and wireless sensors [75]. Overall, the developed system, specifically prototypes I and IV, could generate approximately 10 and 241 watt-hours per year per unit, respectively, under 30,000 AADT.

Jasim et al. [76] developed a new piezoelectric transducer design for road energy harvesting with an optimized geometry, considering the balance between energy collection and mechanical stress concentration [76]. The results indicated that the optimized Bridge transducer design generated an electric potential of 556 V, which could lead to 0.743 mJ of potential energy (open-circuit condition) for a single transducer under an external stress of 0.7 MPa. Laboratory tests on the energy harvesting unit demonstrated that the simulation results were in good agreement with the measured power output.

3. Energy Harvesting for Sensor Applications in Bridges

3.1. Electromagnetic Technology

Electromagnetic generators operate based on Faraday's law, where electric current is induced if an electrical conductor moves relative to a magnetic field. Typically, a coil is attached to an oscillating mass and moves through a magnetic field, generating electricity due to the relative motion between the magnetic field and the coil or changes in the magnetic field [77]. Another alternative approach is to move the relative mass of the magnetic structure while keeping the coil stationary, which can enhance power output and improve the reliability of electrical connections. The amount of electrical energy generated depends on the strength of the magnetic field, the speed of relative motion, and the number of turns in the coil.

In electromagnetic generators, harvesting units are based on hydraulic or pneumatic systems, electromechanical systems, or microelectromechanical systems (MEMS). Small electromagnetic (EM) generators have been developed over the past decade to convert environmental energy sources (mainly mechanical vibrations) into electrical energy. A number of studies have been conducted at the microelectromechanical systems (MEMS) scale and on a macro scale to improve the efficiency of electromagnetic energy harvesting [78].

Since the electric motor is a speed-induced transducer, its application is preferred in situations where vibrations occur in the structure, such as bridges. Bridges are particularly susceptible to damage due to intermittent dynamic loading and are therefore primary targets for Structural Health Monitoring (SHM) applications. For long-term or continuous monitoring, SHM devices must be placed on, under, or within the structure. This makes maintaining battery power challenging, making devices capable of operating on ambient energy highly desirable [79]. Consequently, some studies have focused on harnessing low-frequency oscillations in concrete and cable-stayed bridges using EM generators.

Sazonov et al. (2009) reported a field test of an EM energy harvester designed with the key criterion that the natural operating frequency of the EM device should match one of the bridge's natural vibration modes. This device generated up to 12.5 mW of power derived from traffic-induced oscillations. Jung et al. studied the feasibility of an EM energy harvesting device for powering a wireless sensor network (WSN) attached on the bridge cable [80]. The concept underwent mathematical analysis, laboratory testing, and field trials. The prototype generated up to 15.46 mW of power when mounted on the bridge's support cable. However, the device suffered from limited output power because surface friction, combined with the relatively large deflection of the spring element, restricted the mass movement [81]. To effectively overcome this limitation, researchers proposed an alternative design using a rotational vibration system instead of a translational one. Kim et al. (2015) integrated a moving mass and a rotational generator in place of the EM inductive elements, allowing the device to be tuned to the frequency of the bridge's support cable [82]. A normalized power output of 35.67 mW was achieved—more than double that of the original design. This would be sufficient to sustain a wireless sensor hub for one or two measurements per day, assuming normal to moderate wind speeds.

By harnessing electromagnetic induction, a continuous AC will be generated. However, the efficiency of electromagnetic energy harvesting is low, and the collected energy is not sufficient to power electronic systems [79].

3.2. Previous Research on Piezoelectric Energy Harvesting for Sensors

Most piezoelectric energy systems for bridge applications rely on cantilever beams, which are designed so that the resonance frequencies of the harvesters match the ambient vibration frequencies for maximum efficiency. Ali et al. (2017) investigated the feasibility of energy harvesting using a cantilever setup and focused on identifying optimal locations to maximize the harvested energy. The vibration of the bridge structure due to moving vehicles is the primary source of energy generation [83]. They concluded that the generated power was directly affected by traffic flow, which varied over time.

Elvin et al. (2009) evaluated the bimorph beam configuration for energy harvesting on a bridge [84]. The authors concluded that there was moderate coupling between the bridge's vibration frequency and the resonance frequency (7 Hz) of the harvesting device. Additionally, the current system would generate approximately 14 mJ and 1.2 mJ when connected and disconnected from an electrical generator, respectively. Erturk and Inman (2011) formulated the vibration-based piezoelectric energy harvesting problem using two different approaches [85]. It was found that the piezoceramic patch could generate 1 mW of power at 25 Hz. Lee et al. (2019) investigated the use of a unimorph-type piezoelectric energy harvester, considering the dynamic behavior of the bridge. The researcher concluded that the developed piezoelectric unit could generate approximately 13.8 V under a cyclic loading of 10 kN [86].

Baldwin et al. (2010) investigated the application of piezoelectric technology on highway bridges using sixteen piezoelectric sensors (PZT-5A). The embedded prototype was subjected to cyclic force loading (square wave) with various load amplitudes and frequencies. In their study, the highest energy output of 1.253×10^{-6} Wh was achieved using a load frequency of 1.5 Hz with an amplitude of 17.8 kN at a mean load of 44.48 kN [87]. Peigney and Siegert (2013) focused on the dynamic energy harvested from vibrations within the bridge structure [88]. The researchers designed a cantilever-type piezoelectric harvester. This prototype specifically targeted one of the transverse bending modes of the bridge at a frequency of 14.5 Hz, and the results showed that a maximum power output of 0.03 mW could be generated from peak traffic intensity.

Zhang et al. (2014) discussed the challenge of energy harvesting for bridges using high-frequency piezoelectric cantilevers. They proposed an innovative spring-mass system with two piezoelectric cantilevers to utilize the impacts of moving masses on the bridges, thereby generating electrical energy [37]. The proposed harvesting device showed better performance than the traditional one, which only used low-frequency vibrations of the bridge. Zhang et al. (2014) simulated bridge-vehicle systems to study the energy harvesting performance, using a piezoelectric system based on cantilevers. The results concluded that vehicles traveling at high speeds produce a wide range of frequencies but reduce the output power. The higher vehicle speed can activate several higher-order vibration modes of the bridge. Furthermore, it was found that the road condition significantly influenced the dynamic loading of the vehicles and the output energy.

4. Conclusion

The energy structure of the world is undergoing tremendous changes today. In addition to traditionally large-scale accumulated energy sources for the development of human society, there is also a growing need for distributed, mobile, and divergent small energy sources. Energy harvesting technologies offer promising ways to generate clean and regenerative energy for various applications. The new technologies emerging in this field rely on two energy sources: specifically, thermal energy (from the sun or the earth) and mechanical energy (from vehicle loading or wind). The preferred energy harvesting technology may vary depending on the operating principle and the focus of the application.

Although the photovoltaic system is the most powerful in terms of the amount of energy generated, there are still challenges when applied to roads regarding vehicle operation and slip resistance [89]. Additionally, the current initial construction cost of the prototype is very expensive for effective implementation, although the benefits it offers cannot be overlooked. The optimization of solar energy collectors in asphalt pavement focused on the materials of the pavement and pipes, the size and layout of the pipes, and the type and flow rate of the fluid. The energy harvesting process, at the same time, offers additional benefits from reducing the pavement temperature and mitigating the urban heat island effect.

Geothermal energy harvesting is considered to be at an advanced stage of development, but it is geographically and geologically limited. From a safety and economic standpoint, using the geothermal piping system in critical areas such as bridges, slope sections, and sidewalks would be more beneficial [90].

Although the energy production for thermoelectric energy is relatively low and the cost is high, the future of thermoelectric energy harvesting from pavements looks promising, with improvements in system efficiency due to the design of the structure and material properties [91].

Finally, different energy harvesting designs using piezoelectric materials can be employed to harvest energy based on pressure or vibrations, as well as sensor applications on roads and bridges. The energy produced is typically small for individual piezoelectric transducers under a vehicle pass. To generate larger amounts of energy, multiple sensor arrays are required under repeated traffic loading.

Energy harvesting provides the potential to utilize environmental energy resources as a means of developing autonomy for electrical and electronic devices, whose applications may currently be limited by the restricted storage capacity, and thus the reliability of conventional batteries. Environmental energy scavenging could be used to extend the lifespan of conventional batteries.

Accordingly, the future research directions that can be suggested include the following:

1) How to reduce the current initial construction cost of photovoltaic systems, when applied to roads regarding vehicle operation and slip resistance.

2) How to improve the efficiency of thermoelectric energy harvesting from pavements.

3) How to use multiple sensor arrays under repeated traffic loading for generating larger amounts of energy.

4) How to extend the lifespan of conventional batteries through environmental energy scavenging.

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